SUNDERLAND POLYTECHNIC

ENERGY WORKSHOP

REPORT NO 4

ENERGY ANALYSIS OF
SOME WAVEPOWER
SCHEMES.

DEPARTMENT OF PHYSICAL SCIENCES

Energy Workshop Report No. 4

Energy Analysis of Some Wave Power systems.

K.G. Smith Research Assistant

R. Harrison Supervisor.

J. Varley Research Officer

September 1977

Telephone

Sunderland 76191

SUNDERLAND POLYTECHNIC

Sunderland Polytechnic

CONTENTS

1) Summary

2) General Comments

2.1) Developments in the technologies.

2.2) Technical Decision making.

2.3) Methodology.

3) The System

4) Results

5) Discussion of Results

6) Appendices.

6.1) Energy Analysis of Salter System.

6.2) Energy Analysis of Other Systems.

7) References.

8) Figures 1 - 23.

1) SUMMARY

Energy analysis is a developing technique which has been applied to nuclear power and to conventional fuels from established and new sources. Although it has produced valuable non-intuitive insights into the energetics of these technologies there is still much debate about methodological problems associated with the technique and about the significance of the contribution which energy analysis can make to the decision making about energy technologies.

The work on wave power reported here is part of a programme of work which will extend the application of energy analysis to the 'fluidic' alternative energy sources (wave, wind, hydro and tidal power). The aim is to contribute in a significant way to the decision making/ technology assessment and R & D planning associated with these technologies as well as to address some of the methodological criticisms which have been made of the technique.

The main conclusions from the first stage of the study are:-

1.1) If energy analysis is to be used in a positive way in the assessment of the potential of a proposed technology it is essential to analyse a wide range of feasible designs and technical options so that those with the best energetics can be identified.

In this study we have found it convenient to use two parameters to characterize designs. These are:-

a) an energy ratio.

b) the percentage of the available energy which the design entracts. Wave power extraction efficiency.

When a graph is plotted for a range of feasible designs using these two quantities as axes all the designs are observed to lie below a limiting curve. The designs on the limiting curve are those with the best energetics. A comparison of the limiting curves of different families of wave generators should highlight the inherent physical differences between the families in rather the same way that thermal efficiency characterizes inherent physical differences between heat engines.

This comparison could be a useful part of the decision making which will precede the next stage of the U.K. wave energy programme. In making the choice of which families of devices to develop further (if any) the family with the best energetics should be a strong contender.

1.2) The energy ratio and energy pay back times for Salter 'duck' designs are reasonable. There are designs with energy ratios of 13.1 (this is above the rule of thumb 10.1 threshold for economic viability) and the times required to payback the original energy invested are of the order of 1 yr.

1.3) The energy output /m of the duck string can be increased by increasing the percentage of available energy extracted and this requires an increase in the duck size, in the power limit of the machines and hence in the cost. When the net energy produced by the system is calculated it is found that there is a point beyond which this declines even though the percentage of available energy entracted is still increasing. Using the assumptions of this analysis the peak in net energy production occurs at 55% of available energy entracted.

There can be no benefit in pursuing increased percentage of entraction beyond this limit because designs with lower percentages of extraction will produce the same amounts of net energy at lower costs.

One of the aims of energy analysis has been to set absolute energetic limits on the energy resources exploitable by a technology. Previously the limit has been that of zero net energy. However the determination of points of zero net energy has never been considered too important outside of energy analysis circles because it is usually felt that a conventional cost analysis of such systems would show them to be hoplessly uneconomic before the point of zero net energy is reached i.e. if the economics is right then the energy analysis must be right. It is clear now that the limit of a technology interms of exploitable resources is determined by the point at which the net energy goes through a max and begins to decline and that this will occur for systems which have significantly lower costs than those which produce zero net energy.

The energy analysis has unearthed a significant non-intuitive factor which sets the limit to the exploitable resources made available by a technology. It is likely that parametric energy analysis of the type reported here would indicate a similar limit in the cases of a wide range of conventional as well as alternative energy technologies. It would seem to be important to perform energy analysis of this type so that it will be possible to test whether proposals lie on the right or the wrong side of the limit.

1.4) In designing a wave energy supply system a compromise must be struck between choosing a design which has a good energy ratio (and hence low costs/unit) and a design further down the limiting curve which has a lower energy ratio (and hence higher costs/unit) but which makes better use of sea room (higher total output).

There are many ways in which this could be done depending on relative evaluations of system costs and the utilization of sea room.

The following three are interesting examples.

a) A system utilizing designs which have the highest energy ratios (and hence lowest unit costs). There are designs on the limiting curve with energy ratios of 13:1 which extract 20% of the available energy.

b) A system utilizing designs on the limiting curve with energy ratios of 10:1. These are just on the limit of economic viability but make better use of the sea room extracting 40% of the available energy.

c) A system utilizing designs on the limiting curve with with energy ratios of 5:1. These are probably below the limits of economic viability at the present time, but make maximum net fuel savings and hence best use of sea room.

The details of these systems are summarized in the following table.

DESIGN		For a 500 km system			
Energy Ratio	% of available energy extracted	Net * energy mtce/yr	Fuel † saving mtce/yr	Accumulated capital cost	Capital cost/ton of coal capacity
13:1	20	10.5	32	£5,000 x 10^6	£150
10:1	40	20	63	£16,500 x 10^6	£270
5:1	55	25.5	82	£31,600 x 10^6	£385

---

* This assumes that the electricity is supplying increased demand and is competing with fossil fuels at the point of use in low grade heating applications.

† This assumes that the electricty is used in a way which saves the burning of fossil fuels in thermal stations.

This study has not been primarily concerned with financial appraisal and the cost estimates have been simply obtained from the energy requirements by dividing them by an energy intensity. They give no more than a guide to possible financial costs. Even so it is interesting to compare them with the revised costings of 'Plan for Coal'. Here a capital investment of £3,150 x 10^6 is required to provide a 42 mtc/yr capacity, this is £75/tonne of coal capacity. Provided that it is borne in mind that miners wages'are the major factor in coal costs it seems that assessing wave power simply on a fuel saving basis may provide sufficient economic justification for proceeding with the programme.

1.6) There is nothing in the energy analysis of this system which would militate against a second phase in the wave power programme.*

---

*This para. and para. 1.2 are considerably at variance with the results and conclusions reported by Musgrove[1] which were based on an unrealistic design of wave power generator. There is no unique energy ratio for each type of energy resource; the energy ratio depends on the way in which the resource is exploited i.e. on the technologies and particular designs which are employed. It is not difficult to select a bad design (i.e. far below the limiting curve) and use energy analysis to present the technology (and the potential of the energy resource itself) in a bad light. A more productive approach is to use energy analysis to explore the potential and limits of the technology. (See para. 1.1)

2) GENERAL COMMENTS

2.1) Developments in the Technologies

Before 1973 wave power was very much an underdeveloped technology. This is not because of a shortage of ideas. Between 1856 - 1973 there have been a total of 413 patent applications in the combined category of wave and tidal power, of these about 340 involve some extraction of wave energy (some are combined wave and tidal).[2] Recently some small low efficiency devices have been built and marketed as lighting buoy in Germany. These had outputs of 500 watts or less. The main pre-73 activity has been in Japan where Masuda has maintained an interest in the technology since 1945.[3] This was firstly as means of absorbing wave energy in floating break waters and then as a power source. British interest dates from around 1973. S.H. Salter first turned his attention to wave power in Sept. 1973 and had contact with the new department of Energy in December.[4] Sir Christopher Cockerell became interested in wave power in 1972 and did some experiments in conjunction with the CEGB in 1975.[5] The first published official statement on wave power possibilities came from the C.P.R.S. in July 1974.[6] Subsequently Salter was awarded a contract by the D.T.I. to develop his wave power ideas and a study was carried out at NEL on the techno-economic potential of wave power in the U.K. context[2]

Wave power is currently being funded at a significant level in both the U.K. and Japan. In the U.K. the government are funding directly work on four families of wave generator.[7-11]

a) The Salter 'Duck' developed by Dr. S.H. Salter of Edinburgh University. This design is undergoing tank tests to determine its response to realistic wave spectra. Also Lanchester Polytechnic under contract to Sea Energy Associates are building and testing scale models. Tests on a 1/10th scale model are about to commence.

b) The Cockerell contouring raft was first conceived in 1972 and a company, Wave power Ltd, was formed in 1974 to develop the concept. Tank tests on 1/50th scale models are being carried out by British Aircraft Corporation.

c) Air turbine devices generically similar to those pioneered by Masuda are being developed at N.E.L. where tank tests are in progress of 1/100 scale models.

d) HRS Rectifier is being developed by the Hydraulics Research Station where tank testing of 1/30th scale models is in progress.

In addition to these devices the government are jointly funding, with the Vickers Engineering group, research into fully submerged forced resonance devices.[12] Also the SRC are funding research by Professor M.J. French at Lancaster University into a tube pump wave energy device.[13]

There are two main developments in Japan.

a) Masuda air pressure buoy is now undergoing sea trials.

b) Mitsui engineering and shipbuilding are testing a resonating device similar in principle to those being considered by Vickers.[14]

2.2) Technical decision making and Technology Assessment

The aim of the current U.K. wave energy programme is to develop the engineering research to the stage where the performance of the designs under reasonably realistic conditions is sufficiently well understood that reliable economic appraisals can be attempted. The first stage in the programme should be completed in late 1978 and a decision will be taken on whether to proceed on a further programme of work concentrated on one or two devices. Provided the assessment of the potential economics of wave power is sufficiently promising to justify continuation then the competing designs must be ranked in some way so that the most promising can be chosen for further developments.

Decision making associated with energy technologies is made in a situation of high uncertainty (particulary in the early stages of development). We recognise that 'selection of strategies under uncertainty conditions requires the application of judgement opinion, belief subjective estimates of the situation plus whatever objective data is available'[15] and would never be so naive as to suggest that any one form of assessment, be it energy analysis or any other, should be the sole basis of decision making. A range of criteria are used (admittedly not all ascribed the same weight by different groups). For instance:- financial cost, opportunity cost of resources employed, amount of employment generated, balance of payments costs, market size and environmental impact are all factors which are discussed even in the early stages of the development of a technology. This is reasonable, rational decision making must attempt to reduce uncertainty by accumulating significant relevant information by which the technology can be assessed.

We feel that the work of Chapman and others has established a prima facie case that energy analysis does give significant non-intuitive insights into energy technologies and so deserves to be included in the decision making/technology assessment process. The aim of this study has been to support this case by firstly developing a methodology which is appropriate to the analysis of proposed systems and then use this to assess the extent to which energy analysis can contribute to the decision making/technology assessment of alternative energy sources.

2.3) METHODOLOGY

The Wave energy incident at any location fluctuates in terms of power availability and conversion systems are designed to convert to electricity some fraction of the total mechanical energy available in the waves. A techno-economic decision is taken to reject the remainder of the energy because its infrequent occurence would make it uneconomic to collect.

This is a general rule which applies to the choice of an extraction technology; a techno-economic decision is taken about the percentage of the resource to extract be it an oil well, a coal mine, a hydro-power scheme or a wave energy system.

In the case of wave power conventional fuels are not required directly in the generation of the electricity but they are required to fabricate machines and structures which comprise the technology and in this sense fossil fuels are being used to produce electricity. This implies that there are two ways of assessing the efficiency of the devices used to generate the electricity. These are:-

a) Percentage of available energy extracted

This is a conventional mechanical efficiency which because the power availability fluctuates on a daily and seasonal basis is defined as:-

$$\frac{\text{Total output from a device over an operating season}}{\text{Total wave energy incident on the devices in that location.}}$$

Calculation of this quantity requires a knowledge of

i) The total energy incident at the chosen location derived from wave statistics.

ii) The response of the device in converting mechanical motion of the waves to mechanical motion of the device. This is derived from wave statistics together with tank test or actual performance data.

iii) The mechanical efficiency of machinery involved(hydraulics and alternators). Also any distribution losses.

b) Energy ratio

This is a fossil fuel utilization efficiency defined as either

$$\frac{\text{the total output summed over the life time of device}}{\text{The energy required to build the device.}}$$

or

$$\frac{\text{the output of the device for one years operation}}{\text{the sum of energy requirements for all the components which is accounted to one year's operation.}}$$

Both of these definitions are equivalent. The second is perhaps marginally easier to use.

The calculation of this quantity requires a knowledge of (ii) and (iii) above together with (iv). The energy requirements of all the individual components determined from either physical data i.e. the masses of materials etc. required plus estimates of process energy and transport energy where appropriate, together with cost data of manufactured components.

v) A data base of specific energy requirements or energy intensities to convert (iv) to energy requirements.

iv) Estimates of the lifetimes of components.

The percentage of available energy extracted is a valuable index of performance but since the energy in the waves is not a scarce resource it has no direct significance as an indicator of merit. It does however have implications for the utilization of non-energy resources which may become scarce. In this case shortage of sea frontage will limit the ultimate capacity of any wave power system.

The energy ratio has a significance as an indicator of merit as the energy requirement represents scarce resources consumed.

By determining energy ratios and percentages of available energy extracted for a wide range of designs graphs can be plotted and those designs which have the best energetics identified.

2.3.1) Energy Payback times

The time required to payback the initial energy required to establish the system is given by:-

$$\frac{\text{The total initial energy requirement of the system}}{\text{The total yearly output of the system.}}$$

2.3.2) Net Energy

Considering those designs with the best energetics to be the likely ones from which wave energy systems will be built it is possible to determine the net energy saved by the system. Also the way in which this varies with the percentage of available energy extracted by the system.

There are two possible limiting assumptions about the way in which the energy is used which need to be made before the net energy saved can be determined. These are:-

a) That the electricity is used to supply increased demand and is substituting for fossil fuels at the point of use in low grade heating applications. In this case the net energy saved.
= The annual output of the system - energy requirement attributable to 1 years operation.

b) The electricity is used in a way which saves the burning of fossil fuels in thermal stations. In this case the net energy saved
= 3 x the annual output of the system - energy requirement attributable to one year's operation.

In practice the situation will be somewhere between these two limits.

3) The System

This section reviews the sources of data used and the assumptions which were made about the system so that the quantities (i) - (vi) could be calculated.

The system considered consists of a floating duck string containing onboard hydraulic and electrical machinery, a mooring system, sea bed electrical equipment and cables plus land based equipment at landfall. The motion of the ducks with respect to the backbone is converted to electricity via a flow of hydraulic fluid by hydraulic pumps which are similar in design to the hydraulic wheel hub motors of large vehicles. Each pump has a power capacity of 100 kw and a number will be required for each duck. High speed hydraulic motors drive alternators of 500VA capacity and step up transformers convert the electricity to 11 kv prior to transmission to the sea bed by flexible submarine cable. This cable follows one of the parafil mooring cables. Transmission to shore is assumed to be electrical and both AC and DC systems are considered. A sea bed processing station converts the 11 kv AC into 275 kv AC or rectifies it to $\pm$ 100 kv DC.

Overhead transmission to a remote load centre has also been considered and can be included in the analysis. In a limited study of this type it is different to speculate on the transmission requirements of a wave energy system where different sections will have power landfalls in different locations all different distances from load centres and grid access points. The sources of data on the system are:-

3.1) Performance of devices

These are quantities (i) and (ii) mentioned in 2.3 above. At the time of writing the latest estimates of the output of a Salter duck system operating in the N.E. Atlantic are those of Mollison etal[16]. These figures are based on a detailed analysis of spectral data from Ocean weather Ship/India. Outputs are derived from duck diameters in the range 6 to 18 meters and for power limits 50, 75, 100 and 200 kw/m. Fig. 1. Shows the outputs derived by Mollison converted to GJ/yr. Mollison does not include in this calculation the conversion and transmission efficiencies of the hydraulic and electrical system so that the energies shown in Fig. 1. are the mechanical energies input to the hydraulic system and the total energy available, which is the sum of the incident wave energy over the whole season.

3.2) Efficiences of Components

This is quantity (iii) in 2.3 above.

Reasonable efficiences have been assumed for the different stages in the conversion chain and there are shown in Table 4.
The efficiencies for the submarine cables are quoted for 60 km lengths. The efficiency of the overhead transmission system to load centres has not been included. These losses are not peculiar to wave power systems and are not generally included when specifying the output of other types of power station. In any case the efficiency of transmission is typically high and the effects on the electrical output is within the error of the analysis.

The overall efficiences used were

For the A.C. system $76.8 \times (0.97 \frac{Ls}{60})$ %

For the D.C. system $74.45 \times (0.997 \frac{Ls}{60})$ % $\left(1 - 0.003 \frac{Ls}{60}\right)$

Where Ls = length of Submarine cable in km.

By combining the information in 3.2 and 3.3 the output /m of ducks of different sizes and different power limits can be determined, together with the percentage of available energy extracted.

3.3) Materials requirements of the duck string

The duck string consists of a series of Salter duck sections mounted on a semi-rigid backbone. The backbone is of tubular concrete sections held together under tension by a central parafil cable. The external surfaces of the duck sections are coated with some material which has the properties of preventing fouling by marine growths.

a) Displacement of the duck string

In order to determine the quantities of materials required it is necessary to estimate the displacement of the duck string. Infact this provides an upper limit to the weight of materials required since some of the displacement could be provided by flooding chambers within the structure with sea water. However it is likely that any reduction will be made up by additional strengthening of the backbone.

The ducks float almost completely submerged so that a good approximation for the displacement may be obtained by calculating the displacement of a fully submerged cylinder of diameter D. Where D is the duck stern diameter.

Displacement /m length = Vol of 1m length x density of sea water.

1.03 tonnes /m^3 = density of sea water.

Displacement /m of frontage of duck string

$$= 0.809\ D^2 \text{ tonnes /m}$$

b) Concrete and Steel requirements

The displacement is provided mainly by the materials composing the duck sections and backbone, but the onboard machinery does contribute. This is estimated later and has to be subtracted from the displacement to give the total weight of materials. The mass of machinery is a small fraction of displacement.

Foot Note: The displacement of a floating structure = weight of sea water displacement = dead weight of the structure

Metric tonnes are used throughout 1 tonne = 10^3 kgs.

It is generally assumed that wave generators will be built of some form of reinforced concrete. The amount of steel reinforcement required is important to overall energy requirement and is an important design parameter.

The backbone sections are assumed to contain 5% by weight of steel reinforcement (Salter)[17] this figure which is typical of reinforced concrete beams is required because of the large bending moments which the backbone can experience. The duck sections on the other hand experience only small stresses so that only 2% by weight of steel reinforcement is required.

A standard mix for strong concrete was assumed.[18-19] If the displacement is equally divided between duck section and backbone then the total mass of concrete as a function of duck stern diameter is $0.9651\ (0.81D^2 - 0.0369D) - 0.98W$ and the total mass of steel as a function of duck stern diameter is $0.035\ (0.81D^2 - 0.0369D) - 0.02W$. Where W = Weight of onboard machinery.

These are shown in in Table 1.

c) The quantity of parafil required

Parafil is a fibrous plastic material manufactured by I.C.I. The quantity required depends on the tension which the central cable is required to withstand. The duck string bending moment at which the backbone sections begin to separate and at which the backbone ceases to be rigid is proportional to the product of the cable tension and backbone diameter. The backbone breaking bending moment will probably be chosen to be proportional to the displacement of the structure and this is proportional to D^2.

Bending moment $\alpha\ D^2\ \alpha$ D x cable tension

quantity of parafil required α cable tension α D

It has been estimated in the case of 16 m duck that a cable of cross sectional area of 0.129 m^2 is required this gives a weight of 0.129 tonne/m.

Hence the quantity of parafil/m $= \dfrac{0.129D}{16} = 0.00806$ D. tonnes

d) Anti fouling Coating

The most likely form of anti fouling coating is celmar, a plastic material manufactured by British Celanese. The mass can be estimated by assuming a coating thickness of 0.005 m over a surface of circumference 5.76 D m assuming a density of 1 tonne/m^3 gives a mass of 0.0286 D tonne/m.

Table 1 in the appendix shows the quantities of materials required.

Note: An alternative to the celmar coating is 0.25 mm of Cupro Nickle (Cu: Ni, 70:30) which prevents fouling by means of its toxicity. The density is 8.9 tonnes/m^3 and gives a mass of 0.0128 D tonne/m and an energy requirement of 25% of the celmar coating.

3.4) <u>Mooring requirements</u>

Because the duck strings are linked to the sea bed by a submarine cable the duck strings are required to keep station fairly precisely so that some form of mooring is required. This will have to restrain the duck string against forces exerted by winds and currents together with the effect of the waves, which in most cases tend to push the ducks towards the shore.

The mooring system presently envisaged will probably utilize parafil cables to connect the duck string to the sea bed via an intermediate buoy.[20] This increases the elasticity of the mooring system and prevents damage to the mooring system or duck string when sudden extreme forces are experienced, as may happen during storms.

The mooring system will be designed to withstand forces up to 5 tonnes/m of frontage. Forces greater than this will submerge the buoy and the mooring system will 'give'. If the cable makes an angle of 45° with the sea bed the buoy will require a buoyancy of 5 tonnes/m and the cable will experience forces $5\sqrt{2} = 7$ tonnes. Therefore cables with tensile strengths of 10 tonnes would be a reasonable choice to serve 1 m of frontage. Since parafil has a tensile strength of 4.65 tonnes/cm^2 this requires a cable of 2.15 cm^2. For the depths presently being considered the cable length required is 100 m which gives a parafil requirement for mooring of 0.0215 tonnes/m.

The buoy is assumed to be a fabricated steel structure where the steel represents 5% of the fully submerged displacement. The requirement of steel is therefore $\frac{1}{20}$ buoyancy = 0.25 tonnes/m

3.5) <u>The hydraulics electrical system requirements</u>

Cost estimates for components of the electrical system were taken from Roberts[21] and Whittington[22]. The costs given in these papers are in 1975£. These are deflated to 1968 values by using a deflator of 207.1.

a) <u>The A.C. scheme</u>

Table 5 in the appendix lists the costs of the components required for a system utilizing A.C. transmission with a power limit of 50 kw/m. The Roberts and the Whittington costs both refer to an 8km duck string. These costs together with the costs/m of frontage are shown in Table.

b) <u>The D.C. scheme</u>

Table 6 in the appendix lists the costs of the components required for the D.C. scheme again using Roberts and Whittington as source and a system with a 50 kw/m power unit.

c) Systems with different Power limits

Power limit is an important design parameter in the wave power system and it is essential to consider systems other than those with power limits of 50 kw/m. To do this it was assumed that the costs of the hydraulic and electrical system increases linearly with the power limit. This assumption will be reasonable if increase in power limit is achieved by using more of the same types of component - i.e. multiplying the numbers of hydraulic pumps - alternators etc. installed rather than changing the unit size of the component. The machinery in the duck string consists of large numbers of components of small unit size and the increase in power limit can conveniently be achieved by simply installing more per metre of frontage. Similarly the most convenient power capacity for submarine cable links and land lines are well established and an increase in power limit will simply require a multiplication of transmission components.

d) Weight of the Duck String Machinery

As mentioned earlier(3.3) before the materials requirement of the duck string can be estimated the displacement must be corrected for the small amount provided by the onboard machinery.

The heavy machinery on the duck string consists of hydraulic pumps, hydraulic motors, alternators and transformers. The weights of the hydraulic components were obtained from the power rating and kg/kw data from manufacturers specifications. 1968 Census of production report on Electrical Machinery lists the output of alternators and transformers in terms of both weight and price. This enables the weight to be determined from the cost estimates deflated to 1968.

The weight of on board machinery $W = 1.597 \frac{P}{50}$ tonnes/m

3.6) The data on specific Energy requirements

There are three main sources of data of the energy requirements of materials and components used in this study.

a) Energy requirements/mass, materials

There is much published work on the energy requirements of important materials This is mainly based on process analysis. These are referred to at the appropriate place.

b) Energy Intensities of important components (MJ/£ or KWh/£)

The main source of these is the Open University analysis of the 1968 Census of production.[23] This produced Energy intensities in terms of total direct and indirect energy required to produce products per unit of output for all of the industries in the census. In using these it must be assumed that item considered is typical of the industry, and cost estimates must be deflated back to 1968.

c) Energy Intensities of Electrical Components

These are obtained from a detailed study of the 1968 Census of production report on the electrical machinery industry[24] This has yielded energy intensities for product subgroups within the industry.

The energy requirement data is included in the tables in the appendices as are all of the sources.

3.7) Lifetimes of Components

The reinforced concrete structure is assumed to have a lifetime of 40 years. This is easily comparable with the lifetime of ferrocement ships. The antifouling coating and parafil cables are replaced every 6 years. The hydraulics are assumed to be replaced by new equipment every 6 years as recommended by Salter. The electrical equipment is assumed to be replaced by new equipment after 15 years.

These assumptions probably over estimate the machinery requirements of the system and hence the energy requirement. The energy required to recondition hydraulic pumps is probably only a fraction of that to make new ones.

It was assumed that the replacement of components occurs during the summer months when output is expected to be low, and that this would not reduce the overall output of the system. It was also assumed that there were no equipment failures during the winter months which would reduce the output.

3.8) Models of the Energy Requirement

These are obtained by multiplying masses of components by specific energy requirements, or by multiplying cost estimates by energy intensities. The details of these calculations are shown in the Tables in the appendix

a) Duck String

Total energy requirement.

$$2.505\ D^2 + 6.35\ D - 3.78\ \frac{P}{50} \quad GJ_t/m$$

Energy requirement attributable to one years operation is

$$0.063\ D^2 + 1.075\ D - 0.0935\ \frac{P}{50} \quad GJ_t/m$$

b) Mooring energy requirement

15.13 GT_t/m

c) Hydraulic and Electrical Components

i) AC

Total $\frac{P}{50}$ $(200.3 + 8.59\ L_s + 0.714\ L_1)\ GJ_t\ /m.$

Energy requirement attributable to one year.

$$= \frac{P}{50}\ (20.58 + 0.573\ L_s + 0.0286\ L_1)\ \ GJ_t/m.$$

ii) DC

Total $= \frac{P}{50}\ (302.9 + 3.489\ L_s + 0.213\ L_1)\ \ GJ_t/m.$

Energy requirement attributable to one year.

$$= \frac{P}{50}\ (28.56 + 0.233\ L_s + 0.0117\ L_1)\ \ GJ_t/m.$$

For the whole system this becomes

i) Total $= 2.505\ D^2 + 6.35\ D + 46.22P + P(0.172L_s + 0.014\ L_1)GJ_t/m$

Attributable to one years operation.

$$= 0.063\ D^2 + 1.075 + 0.41P + P(0.0115L_s + 0.005L_1)\ \ GJ_t/m.$$

what about mooring + (assumed 15yr life)

ii) Total $= 2.505\ D^2 + 6.35D + 5.98P + P(0.7L_s + 0.04L_1)\ GJ_t/m.$

Attributable to one years operation.

$$= \cancel{2.505}\ D^2 + \cancel{6.35}D + 0.57P + P(0.0046L_s + 0.00023L_1)\ GJ_t/m.$$

Where D = duck stern diameter in metres.
P = Power limit in kw/m
L_s = length of Submarine cable in km.
L_1 = length of land lime in km.

† DC System (Annual GER)

$$= 0.063D^2 + 1.075D + 0.57P + P(0.0046L_s + 0.00023L_1) + 1.02$$

4) RESULTS

Using the models developed above total energy requirements and the energy requirements accountable to one years operation have been calculated for duck designs with stern diameters 7-18 m and power limits of 50, 75, 100 and 200 kw/m.

The transmission systems considered are

a) 40 km submarine transmission. This is about the transmission distance required for a duck string off the Hebrides and power landfall in Ross and Cromarty. A land line to Glasgow has also been included in this calculation.

b) 20 km submarine transmission. This was chosen as a typical submarine transmission distance for an extended system.

Both ac and dc options have been considered.

Figs 2 to 10 show energy requirements as a function of duck stern diameter for a variety of systems Figs.10 to 15 show payback times as a function of percentage of energy extracted.
Figs. 16 to 21 show energy ratios as a function of percentage of energy extracted.
Figs. 22 & 23 show pie charts of the contributions to the energy requirement of a 16 m duck with 50 kw power limit and 40 km submarine transmission.

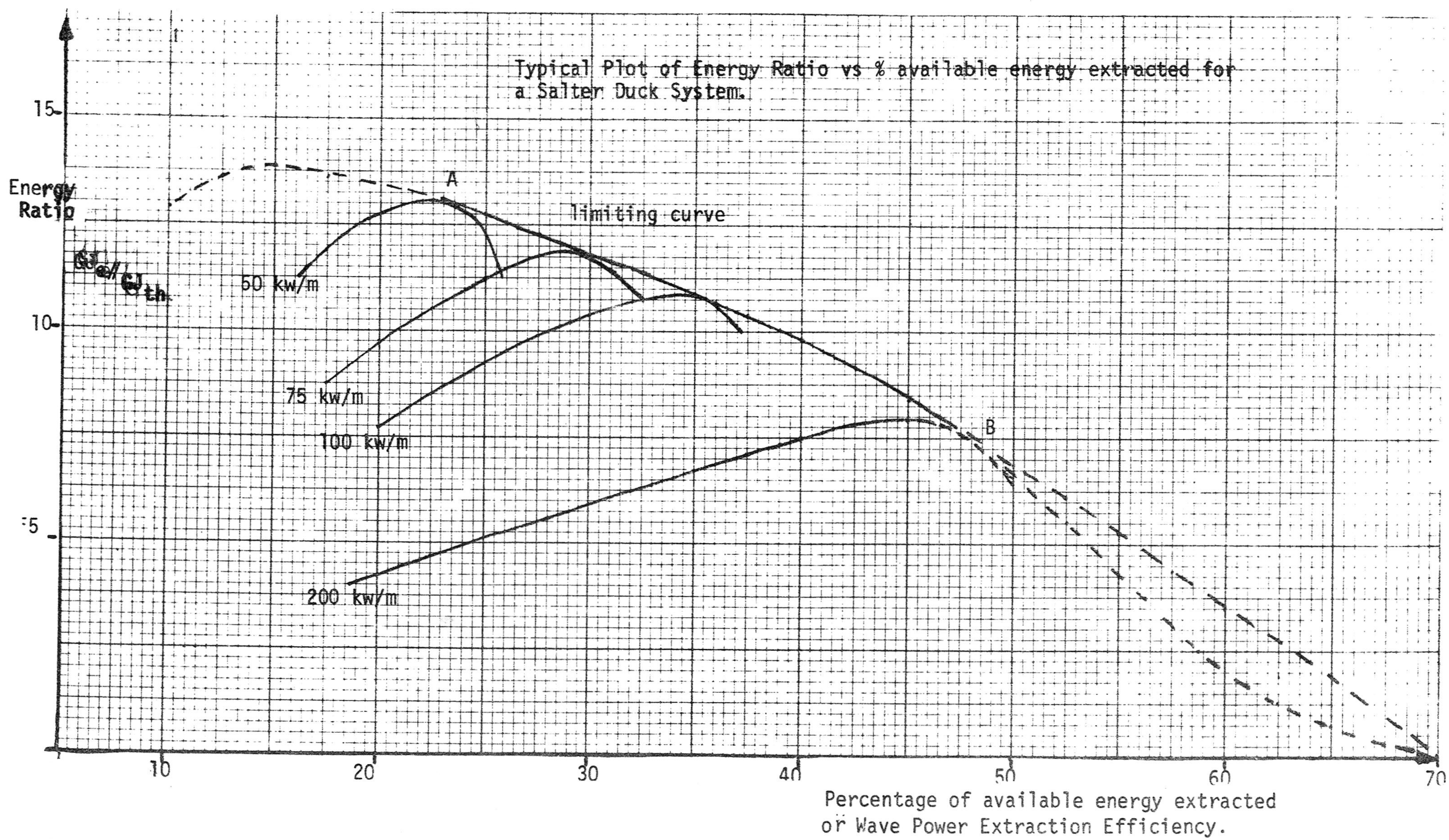
5) DISCUSSION OF RESULTS

5.1) General Comments

As mentioned earlier (3) it is difficult to decide the extent to which over land transmission should be included in a study of this type. In a full study of the relative economics of competing energy sources transmission of power should be and is considered. Then however account must be taken of the facts that while wave power sources are remote from load centres, nuclear power stations require coastal sites and can expect increasing delays in the planning examinations. Also the coal industry is dependent on the rail freight network which may need extension if new coal fields are exploited. North Sea oil and gas fields are also remote and require expensive special distribution systems. When discussing the economics of a power source initially costs are quoted at mine gate at the power station or at land-fall for offshore sources. We shall do the same here. Beyond observing that the landline costs are an important but never dominant factor in the energy requirement over the large distance considered here we leave the discussion of transmission to a later phase of the study.

The differences between AC and DC transmission can be seen from the figs. The cross over point at which the AC and DC systems have the same energy requirement is at about 20 km. Below 20 km the energy requirement of the AC system is least and above 20 km the energy requirement of the DC system is least. Submarine transmission is clearly seen as a major contributor to the energy requirement.

FIG. A


Typical Plot of Energy Ratio vs % available energy extracted for a Salter Duck System.
Energy Ratio
GJ_e/GJ_{th}
15
10
5
A
B
limiting curve
50 kw/m
75 kw/m
100 kw/m
200 kw/m
10
20
30
40
50
60
70
Percentage of available energy extracted or Wave Power Extraction Efficiency.

Other systems of submarine transmission should be examined. It is interesting to note that if some form of energy storage system could be devised which would operate out at sea in the vicinity of the duck strings then the submarine transmission load would be smoothed and the power limit of the submarine transmission could be reduced.

5.2) Curves of payback versus percentage of available energy extracted.

In all cases there are designs with low payback times in the region of 1 year (this compares with payback times of 1.5 - 2.5 yrs. calculated by Chapman[25] for nuclear power stations). Beyond this simple observation there is little more which can be deduced from these curves. Their real value lies in the analysis of energy flows during building programmes. This is intended to be part of a further stage of our programme of work on alternative energy sources.

5.3) Curves of energy ratio versus percentage of available energy extracted.

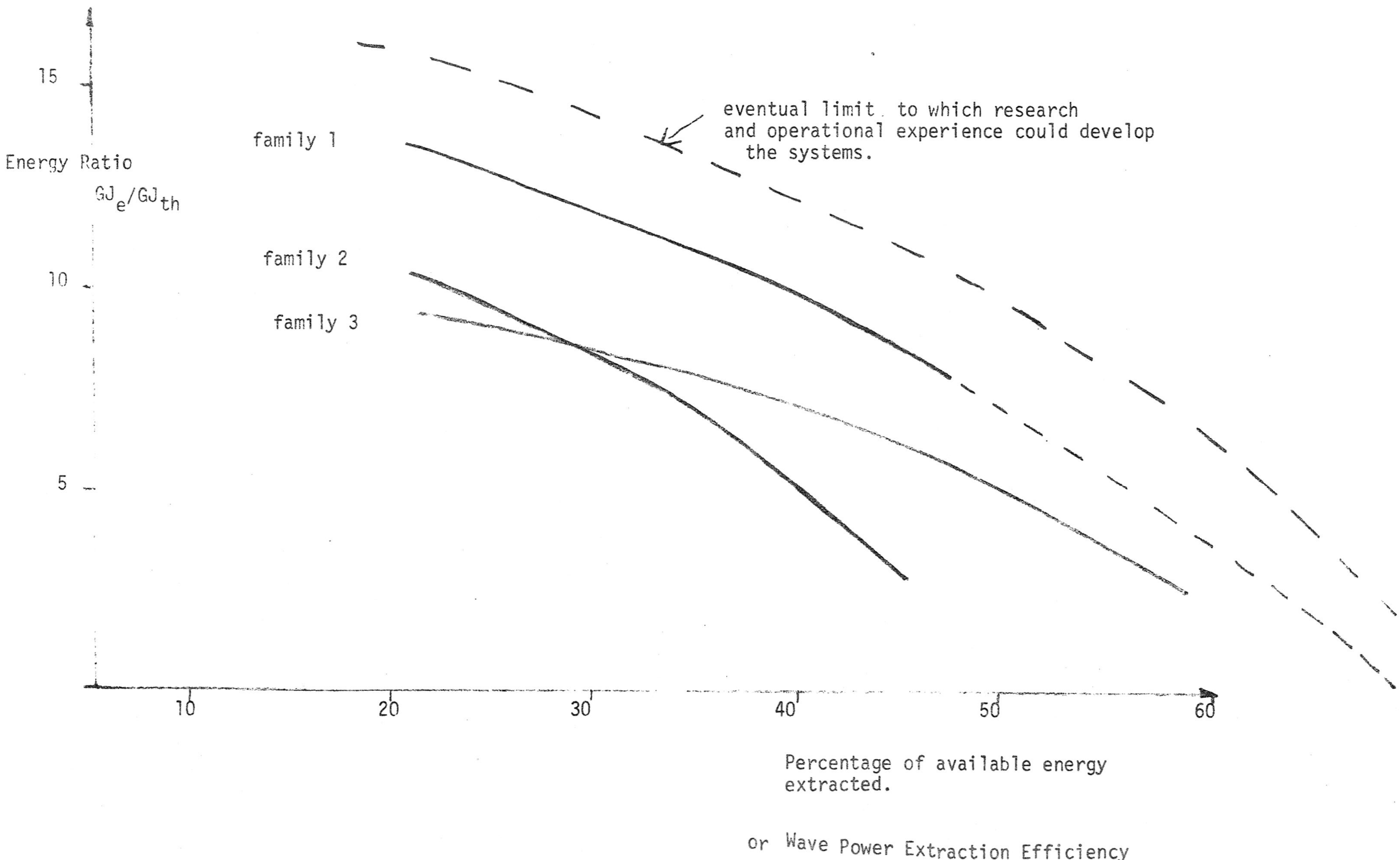
One of the curves computed is selected as typical for further discussion of the significance of these curves. This is reproduced in fig. A.

Here each design is represented by a single point and points representing the wide range of feasible designs considered all lie in the limited region of the graph below the line AB. Several points may be joined together to demonstrate the effect of changing a design parameter. The curves shown are for varying duck stern diameter, however any system parameter could be chosen.

This graph allows the comparison of the utilization of the two resources of fossil fuels and sea frontage, both of which are important when assessing wave power schemes. It shows that there are designs in the region of A (which correspond to small ducks with low power limit machines and transmission) which, while they extract a moderate percentage of available energy, have a higher ratio than designs in the region of B (which correspond to large ducks with high power limit machines and transmission) which extract a higher percentage of available energy. An increase in the percentage of available energy extracted is achieved at the penalty of decreasing the load factor because a higher installed capacity per meter is required if energy is to be extracted in the infrequent conditions of extremely high incident wave energy. Designs in the region of A have the best energy ratio but make inefficient use of the sea room. In constructing a system where a fixed capacity is required with limited sea room available a design with a lower energy ratio and higher percentage of total energy extracted would probably be chosen. The energy analysis ranks the designs lying along the line AB as the 'best' design from which this choice could be made.

In fig. A. an attempt has been made to extend the limiting curve AB beyond that calculated. In the region of A the load factor can be increased by reducing the duck diameter and the power limit, this will increase the energy ratio until a point is reached when extra strengthening must be incorporated in the duck string to prevent it breaking up. This will cause the energy ratio to decline again. In the region of B the percentage of energy extracted can be increased by increasing duck size and power limit.

Fig. B. Limiting curves of competing wave power systems (Speculative)



However this can not go beyond the point of 75% of available energy extracted, as this represents total transfer of wave energy to the ducks and output only limited by losses in the machines etc. It is not clear how the limiting curve will approach this upper limit and two possible curves are shown.

5.3.1) Inherent physical differences

Graphs of this type should provide a useful framework for the comparison in energy terms of different designs and whole families of devices. Since both axis are independent of any parameter peculiar to any wave power system all wave power systems can be plotted on the graph. Each of the different wave power devices (Salter, Masuda, Cockerell, HRS) work on somewhat different principles and these result in inherent physical differences between designs in terms of actual construction requirements and performance. Thus while it would be possible to design both Salter and Masuda systems extracting the same percentage of available energy from the waves (and hence some output/metre of frontage) they would employ different machines, and have structures of different masses and materials. The energy requirement of a system depends upon the physical nature of the technology, sizes of electrical machines, masses of materials required etc. Thus the energy ratios of the two devices will be different and in general the differences between energy ratios will closely reflect inherent physical differences between designs. These physical factors mentioned impose limits on the potential of the technologies and the inherent physical differences between designs which are a consequence of different principles of operation probably have unavoidable implications for the relative economics of different families of devices.

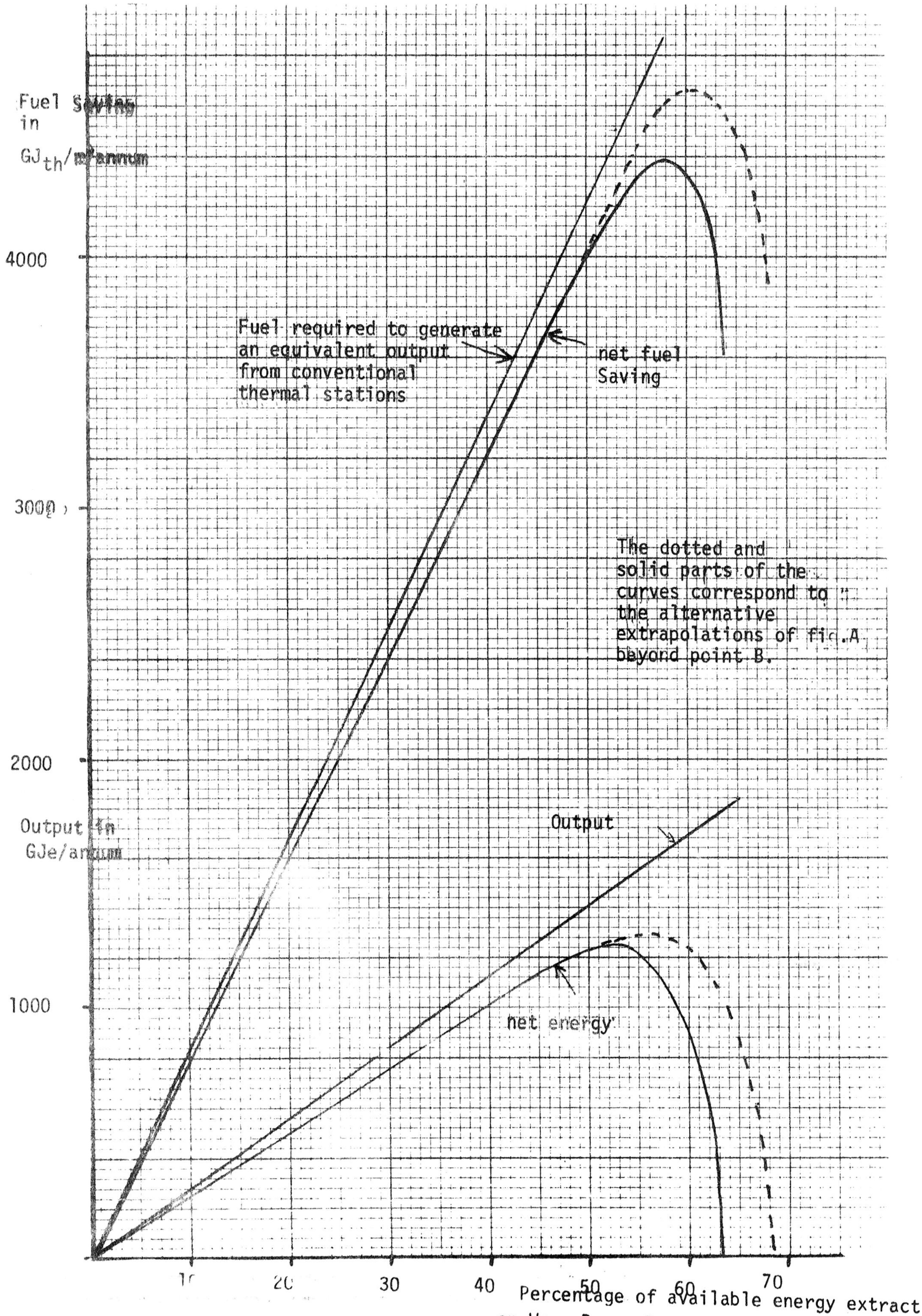
A comparison of different families of wave generators using a plot of this type could be of great value at this stage of the national wave energy programme. The designs of wave generators belonging to different families would probably occupy different (overlapping) regions of the graph and there would have different limiting curves representing the energetically best designs. Fig. B . shows the kind of thing which could be obtained.

When making a choice of which families of device to develop further in a second phase of the programme the family with the best energetics should be a strong contender.

5.3.2) Effect of Energy Prices on choice of design.

The economic viability of a technology at a particular point in time will depend upon the general level of energy prices in relation to other prices, as well as upon the performance of the technology. It seems that at the present time an energy ratio of 10:1 for an energy conversion technology represents a threshold below which economic viability is unlikely but above which it is possible and it may be possible to use this as a necessary but not sufficient condition of economic viability. In this way energy analysis could be of use to design engineers. It should be possible at an early stage of the development of a technology to identify those design concepts which firstly the conditions of energetic feasibility by giving an energy profit and secondly to go further and identify the more limited range of designs which show a potential to satisfy the necessary energy conditions for economic viability. This would avoid the wasting of time on those designs which can never satisfy these conditions.

Fig. C.
Net energy Produced and Net Fuel Saving
for designs on the limiting curve.



Energy analysis does concentrate on a single factor of production and this makes it useful in determining the sensitivity of the costs of a technology to energy price rises. There are two aspects to this which are best illustrated by the following examples.

Firstly suppose that the technologies 1 & 2 in Fig. B are costed at the present point in time and that some non-energy factor (e.g. maintainance) reverses the rankings given by the energy analysis making technology 2 economically more attractive than technology 1. In a situation where energy prices are rising in real terms the significance of energy costs as a factor of production should increase and the significance of non energy factors decline. This would make technology 2 less attractive economically and technology 1 more attractive. In general the rankings given by energy analysis will coincide with those given by cost analysis in the limit of high energy prices in real terms, and also arguably, in a situation where high unemployment of men and machines reduces the opportunity costs of capital and labour.

Secondly when choosing a design from among a group of designs in a single family of devices (assuming that the optimal family has been determined, the Salter system for example) a similar graph to fig. A. could be plotted with the value of electrical output/capital cost of system (calculated using cost estimates relevent to the time of development) instead of energy ratio. It is likely in this case that the rankings of the designs in terms of energy requirement will be close to the rankings given by capital cost. Hence the best economic designs will be in the region of the limiting curve A B. The choice of final design will depend upon the price of energy. Again as energy prices rise in real terms energy costs will tend to become an increasing fraction of the cost of production and capital costs will rise. However the value of the energy produced will rise at a faster rate and the threshold energy ratio for economic viability will decrease and designs with smaller energy paybacks but which extract larger proportions of the available energy will become viable.

5.4) Net energy produced by the system

The net energy produced per m by a range of designs on the limiting curve has been calculated using the two limiting assumptions as to the way in which the energy is used. Designs on the limiting curve are chosen because these have the best energetics and at any percentage extraction the designs on the limiting curve produce the greatest net energy. A plot of wave energy extraction efficiency vs net energy saving for the Salter system is shown in Fig. C.

The form of the curve is interesting. Up to an available energy extraction of 50% net energy is never less than 80% of the output. Between 50% and 65% of available energy extracted however the net energy rapidly falls to zero. There can be no circumstances in which it would make sense to push the percentage of energy extracted beyond 50% as the same net energy could be produced by smaller cheaper designs. It would seem to be important to do net energy plots of this type for all families of devices in the wave power programme.

Also it is probable that a graph of this type could be plotted for a wide range of extraction and conversion technologies. Again this will be a useful thing to do so that the limit to which the technology can be pushed in terms of percentage of resource extracted can be determined.

This point of maximum net energy will be reached significantly before the point of zero net energy which has previously been thought of as the energetic limit. While it must be realised that the point of maximum net energy occurs for designs very much larger than those being considered at present, it is possible that the technology will move in this direction. Calculations should be done to determine the shape of the limiting curve beyond B of Fig. A so that extrapolation need not be used in the determination of the point of maximum net energy.

5.5) Estimates of net energy from extended wave energy systems

Any number of wave energy systems could be proposed representing different techno-economic choices between low cost electricity and good utilization of sea frontage.

Three possible choices are of interest.

a) A system built using designs with best energy ratio and hence lowest costs/unit.

b) A system built using designs with energy ratios of 10:1. These designs could be just on the limit of economic viability.

c) A system built using those designs which extract maximum net energy. This system makes best use of sea room.

The particulars of these systems are shown in Table 3
The costs given here are determined from the energy requirement simply by dividing by an energy intensity of 50 kwh/£ . These cost figures give no more than an indication of possible costs and should not be given any more significance. It is interesting to compare these with the recent revised costings of 'Plan for coal' where a capital investment of £3150 x 10^6 is required to increase the deep mined capacity of the NCB by 42 mtc/yr. This corresponds to a cost of £75/ton of coal capacity, and can be compared with £150, £270, £385/ ton of coal capacity for the three wave energy systems if the energy is used to give max fuel saving. Provided it is borne in mind that miners wages are the major factor in coal costs then assessing wave energy systems on a simple fuel saving basis could give sufficient economic justification for proceeding with the development programme.

Table 1.

G.E.R. of Duck String of Diameter D/meter of frontage.

Component	Type of Material	Weight (tonne)	Energy Requirement GJ_t/tonne	Source	Gross Energy Requirement of component GJ_t/m.
Central Cable	Parafil Plastic	0.0081 D	159.4	*	1.285 D
Antifouling Coating	Celmar Plastic	0.0288 D	159.4	*	4.593 D
Backbone	Concrete 95%	$0.475\ (0.81D^2 - 0.0369D)$	1.22	**	$0.469D^2 - 0.021\ D$
	Steel 5%	$0.025\ (0.81D^2 - 0.0369D)$	46.8	*	$0.947D^2 - 0.043\ D$
Ducks	Concrete 98%	$0.49\ (0.81D^2 - 0.0369D) - 0.98W$	1.22	**	$0.484D^2 - 0.022D - 1.29W$
	Steel 2%	$0.01\ (0.81D^2 - 0.0369D) - 0.02W$	46.8	*	$0.3786D^2 - 0.0170 - 0.94W$
Total		$0.809\ D^2 - W$			$2.28D^2 + 5.78D - 2.13W$
		Construction energy = 10% materials energy requirement **			$0.23D^2 + 0.58D - 0.21W$
		Total			$2.51D^2 + 6.35D - 2.34W$

* Chapman[26]
** Varley[18]

TABLE 2.

GER OF MOORING SYSTEM

COMPONENT	TYPE OF MATERIAL	WEIGHT	ENERGY REQUIREMENT GJ_t/tonne	SOURCE	GROSS ENERGY REQUIREMENT OF COMPONENT GJ_t/m
Cable	Parafil Plastic	0.0215 tonnes/m	159.4	*	3.43
Buoy	Steel	0.25 tonnes/m	46.8	*	11.7
			TOTAL		15.13

* Chapman[26]

Table 3.

% of available energy extracted	Energy Ratio	Energy Req. GJ/m/yr	Energy Req. over 40yr GJ/m	Total Capital Cost £$_{77}$/m	Net Energy Prod. GJ/m/yr	tce m/yr	Fuel Saving GJ_t/m/yr	tce fuel saved m/yr	Mtce fuel saving 500 km	Equiv. net* Const. operating Capacity/ kw/m	Capital Cost/ Equiv. kw	Installed Capacity kw/m	Average load factor
20	14	45	1,800	10,000	530	21	1,660	64	32	17	580	40	40%
40	10	150	6,000	33,000	1,030	40	3,300	127	63	33	1,000	100	33%
55	5	285	11,500	63,200	1,225	46.5	4,340	164	82	37	1,700	300	10%

1 ton of coal = 26 GJ_t

* this is determined from the net output/m.

Table 4

Conversion and Transmission losses

Item	A.C. System	D.C. System	Source
Hydraulics (Motors)	0.85	0.85	- Manufacturers Data -
Alternators	0.96	0.96	Whittington et al
On-Board Transformers	0.98	0.98	"
(D.C.→A.C.) Convertor and Rectifier (A.C.→D.C.)	-	0.95	"
Transformer	0.98	-	"
D.C. Sub. Cable	-	.9972 For a 60km length	"
A.C. Sub. Cable	.9734 For a 60km length	-	"
Terminal Transformation (to Grid Voltages)	0.98	0.98	"

Overall Efficiencies

A.C. System $76.80 \times (0.9734)^{ls/60}$ % $(1-0.03)^{Ls/50}$

D.C. System $74.45 \times (0.9972)^{ls/60}$ %

ls = submarine cable length in km.

NOTE. The Landline transmission efficiency has not been included here. It is small and also any system supplying electricity to the grid will require landlines.

$1^{kwLt}/68£ = {}^{3.6}/2.071$ MJ/75£

Table 5a — Cost of hydraulic/electric equipment for the A.C. scheme

Salter Duck System

Item	* Frontage→ Cost 8,000m £M	1m	Census Group Ind. Group	MJ/75£* En Int.	Total E.Req GJ_t	Life	E.Req. for one year GJ_t	
Motors (Hydraulics)	6.0	750	52	101.06	75.8	6	12.63	e.g. 75.798 ÷ 6 = 12.633
Generators	5.4	675	71*	92.98	62.76	15	4.18	- G.E.R. attributable to one year's life of this component
A.C. Controllers	0.8	100	74	91.52	9.15	15	0.610	
Flexible Busbar	0.2	25	72	136.13	3.40	15	0.226	
On Board Transformers	1.7	212.5	71*	131.00	27.84	15	1.86	
Flexible Cable	0.1	12.5	72	136.13	1.70	6	0.284	
Sea Bed Housing	0.1	12.5	80	103.86	1.3	25	0.052	
Sea Bed Transformer	0.8	100	71*	131.0	13.1	25	0.524	
Circuit Breakers and Protection	0.4	50	71*	104.73	5.24	25	0.209	
					200.3		20.6	
A.C. Submarine Cable per km	0.5	62.5	72	136.13	8.51	15	0.567	Note. These figures are for one km length of submarine cable.
Laying Cost	0.01	1.25	151 Pub.	69.01	0.086	15	0.005	
					8.59		0.573	
A.C. Landline per km	0.061	7.63	64	93.62	0.714	25	0.028	- These are for 1km of Landline.

* Energy intensities are in MJ/75£
Deflator 1968 to 1975 was 2.071

Table 5b

Cost of hydraulic/Electric equipment for the D.C. scheme

Salter Duck System	Cost 8000m £M	1m	Census Group Ind. Group	MJ/75£ EN. Int.	Total E. Req. GJ_t	Life	E. Req. for one year GJ_t
Motors ~~Generators~~	6.0	750	52	101.06	75.8	6	12.63
Generators Motors	5.4	675	71*	92.98	62.76	15	4.18
A.C. Controllers	0.8	100	74	91.52	9.15	15	0.610
Flexible Busbar	0.2	25	72	136.13	3.40	15	0.227
On-Board Transformer	1.7	212.5	71*	131.00	27.84	15	1.86
Flexible Cable	0.1	12.5	72	136.13	1.70	6	0.28
Sea Bed Housing	0.1	12.5	80	103.86	1.3	25	0.005
Rectifier	2.0	250	74	91.52	22.88	15	1.53
Sea Electrodes	0.5	62.5	71*	104.73	6.55	6	1.09
D.C. to A.C. Convertor	8.0	1000	74	91.52	91.52	15	6.10
Sub Totals					302.9		28.56
D.C. Submarine Cable !!! per km	0.2	25	72	136.13	3.40	15	0.227
Laying Cost	0.01	1.25	151 Pub.	69.01	0.086	15	0.006
					3.489		0.233
D.C. Landline per km	0.025	3.13	64	93.62	0.293	25	0.011

6.2) Energy Analysis of Other Systems

Brief energy analysis of some other wave power systems were performed These analyses were based on limited incomplete designs and performance data for only one set of design parameters. The results are presented for the record only and definite comparisons between these systems and the Salter system on the basis of these results in not justified.

a) The Masuda Triangle Buoy

This analysis is based on Masuda etal[3]
This considers a triangle buoy with a sea frontage of 600 m requiring a 6,000 tons of steel for its construction (at a cost of 900×10^6 Yen)
The machinery costs are also given in Yen and are converted assuming $£_{68}1 = 24\text{-}7$ yen.

6,000 tons of steel have an energy requirement of 79.2×10^6 Gwh

$$\text{the yen energy int.} = 79.2 \times 10^6/900 \times 10^6$$
$$= 0.088 \text{ kwht/yen}$$

if this corresponds to the U.K. energy int.

of 212.71 kwht/$£_{68}$

then $1\ £_{68} = 2417$ yen.

Component	Cost in Yen.	$£_{68} \times 10^6$	Energy* Int. MJ/68£	Census Rpt No.	GER $GJ_t \times 10^3$
Steel	900	0.327	765.7	44	250.4
Electrical Machinery	900	0.327	221.4	71	72.4
Maintenance 1 yr	200	0.0827	215.1	80	17.8
2nd - 15th yr	1400	0.579	215.1	80	124.5
				TOTAL	465.1

*Source: Casper <u>etal</u>[23]

The GER per metre = 775 GJ_t

and assuming a 15 yr lifetime the GER attributable to one years operation = 51.7 GJ_t per m.

Electrical output from the traingle buoy Northern Japanese waters was estimated by Masuda to be 151.2×10^3 GJe/yr.

this corresponds to 252 GJe/m/yr.

This gives an energy ratio then of $\frac{252}{51.7} = 4.9$ GJe/GJ_{th}

The payback time is 3.1 yrs.

The percentage of available energy extracted is 13.8% of the total energy available in the region which is 1900 GJe/m/yr (60 kw/m average)

b) Masuda Ring Buoy

These data are taken from Leishman and Scobie[2].

The system considered is a Masuda ring buoy with a diameter of 305 m (1000 ft) producing an average electrical output of 5017 kw $= 158 \times 10^3$ GJe/yr.

Component	Quantity or cost	Unit GER * or Energy int. MJ/75	Report No.	GER $GJ_t \times 10^3$
Steel	£2782 x 10^3 26500 tons	46.8 $GJ/_t$ [a]	-	1259
Shot-blasting	£96 x 10^3	420[d]	-	40
Paint	£300 x 10^3	259	32	78
Fabrication	£462 x 10^3	104	80	48
Super-structure	£1102 x 10^3	104	80	114
Valves	£21 x 10^3	102	52	2
Air turbines	£800 x 10^3	102	52	82
Generators (D.C.)	£480 x 10^3	88.5[b]	71	42
Terminal Eqpt.	£1600 x 10^3	105[b]	71	168
Transmission	£900 x 10^3	100[c]	-	90
Cable laying	£50 x 10^3	100[c]	-	5
Mooring	£40 x 10^3	100[c]	-	4
			Total	1952

Assuming a 15yr lifetime then the GER attributable to one years operation $= 130 \times 10^3\ GJ_t$. this gives an energy ratio of $\frac{158}{130} = 1.1\ \frac{GJe}{GJ_{th}}$ Assuming that the buoy is sited in the North Atlantic the percentage of the available energy extracted = 18%

* Casper et al[23] except a = Chapman[26]

b = Smith[24] c = Average energy intensity for Mech. Eng. d Assumes that all of cost is electricity at 3p per unit.

REFERENCES

1. P.J. Musgrove, Energy Analysis of wave power and wind-power systems Nature, 262, 1976 p. 206.

2. J.M. Leishman and G. Scobie 'The Development of wave power-A Techno-economic study' (Economic Assessment Unit, National Engineering Laboratory, 1976)

3. Y. Masuda, T. Miyazaki, T. Emura, 'Possibility of large electric output by floating type sea wave Electric Generator' (Japan Marine Science and Technology Centre, 1974) See also Y. Masuda 'Study of Wave activated generator for island power and land power'
Paper BX119, 2nd International Colloquim on Exploitation of the Oceans, 1 - 4 October 1974, Bordeaux, 'Study of wave activated generator and future view as an island power source 2nd International Ocean Development Conference, 1972, Preprints Vol. 2 pp 2074-2090 and 'Wave activated generator for robot weather buoy and other use'. Paper at International Colloquium on the Exploitation of the Oceans, March 1971, Bordeaux

4. S.H. Salter, Memorandum and Evidence Select Committee on Science and Technology (Energy Resources Subcommittee) Alternative Sources of Energy. Minutes of evidence (HMSO, 1976)pp 281-292.

5. C. Cockerell, memorandum and evidence, ibid pp. 459-468

6. Energy Conservation - A study by the Central Policy Review Staff (HMSO, 1974)

7. Wave Energy Press Release, April 29, 1976 (E.T.S.U.)

8. S.H. Salter, 'Wave Power' Nature, 249,1974 pp. 720-724.
S.H. Salter, D.C. Jeffrey, J.R.M. Taylor 'The architecture of nodding duck wave power generators' The Naval Architect

   Jan 1976 pp 21-24, S.H. Salter 'The Environmental Aspects of Wave Power' (Dept of Mech. Eng.) University of Edinburgh,1975)

9. R.H.Y. Hancock, etal, memorandum and evidence Select Cttee. on Science and Technology (Energy Resources Subcommittee) etc. pp. 267-281.

10. M. Woolley and J. Platts 'Energy on the Crest of a wave' New Scientist May 1975 pp. 241-243.

11. Memorandum by Hydraulic Research Station and R.C.H. Russell, evidence Select Committee on Science and Technology (Energy Resources Subcommittee) etc. pp. 468-476.

12. The Energy Show, Official Catalogue (Indent International Exhibitions, 1977)

13. ibid

14. New Scientist 24 March 1977, p 702.

15. W.G. Scott, 'Organisation theory' in F.G. Castles etal (eds) Decisions, Organisations and Society (Penguin 1971) p. 24.

16. D. Mollison, O.P. Buneman, S.H. Salter 'Wave Power Availability in the N.E. Atlantic' Edinburgh Wave Power Project Lab. rpt. 15,1975

17. S.H. Salter, Private Communication (1976)

18. J. Varley, 'Energy Use in Large Construction Projects' Sunderland Polytechnic, Dept. of Physical Sciences, Energy Workshop rpt. No. 3, 1977.

19. E.M. Gartner and M.A. Smith, 'Energy Costs of House Construction' Energy Policy Vol. 4. (2) June 1976 pp. 144-157.

20. S.H. Salter, Private Communication. (1977)

21. W.P. Roberts, 'An Economic Study of Wave Power, Hons. Dissertation, Dept. Elec. Eng., University of Edinburgh, 1976.

22. H.W. Whittington, 'Transmission of Electricity from Wave Power Devices' (Dept. Elec. Eng., University of Edinburgh).

23. D.A. Casper, P.F. Chapman and N.D. Mortimer 'Energy analysis of the 'Report on the Census of production 1968'' (O.U. Energy Research Group, ERG006, 1975)

24. K.G. Smith, 'Energy analysis of the 1968 Census of production report on the Electrical Machines Industry' Sunderland Polytechnic, Dept. of Physical Sciences, Energy Workshop rpt. No. 2 1976.

25. P.F. Chapman, 'Energy analysis of nuclear power stations'. Energy Policy Dec. 1975 p 291.

26. P.F. Chapman, 'Energy Cost of materials' Energy Policy May 1975 pp 47-57.

Fig. 1.

Output from a Salter Duck in the N.E. Atlantic - After Mollison. (primary power take off)

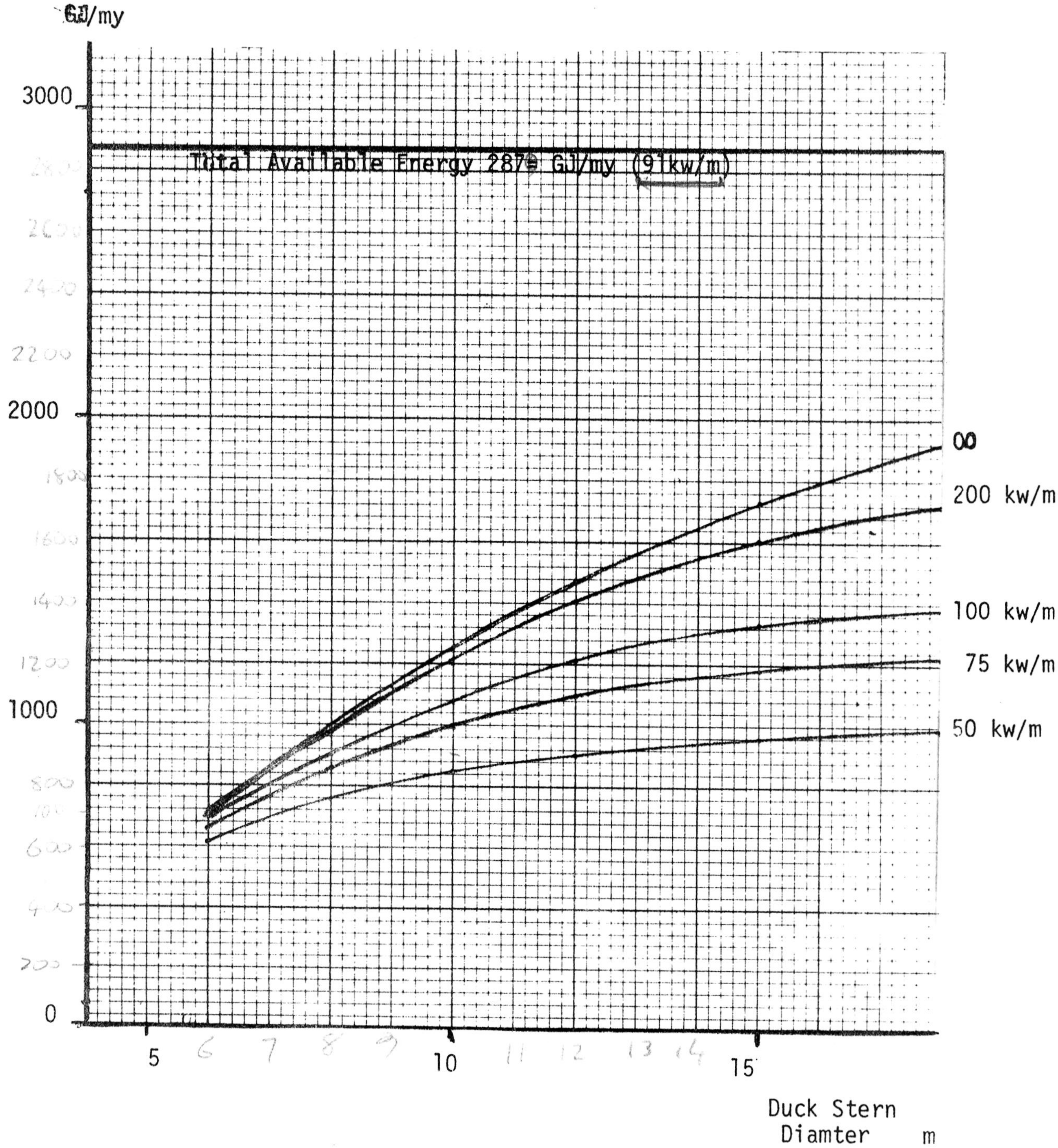


Fig. 2

Initial Energy Requirement of a Salter Duck System - per metre of frontage.

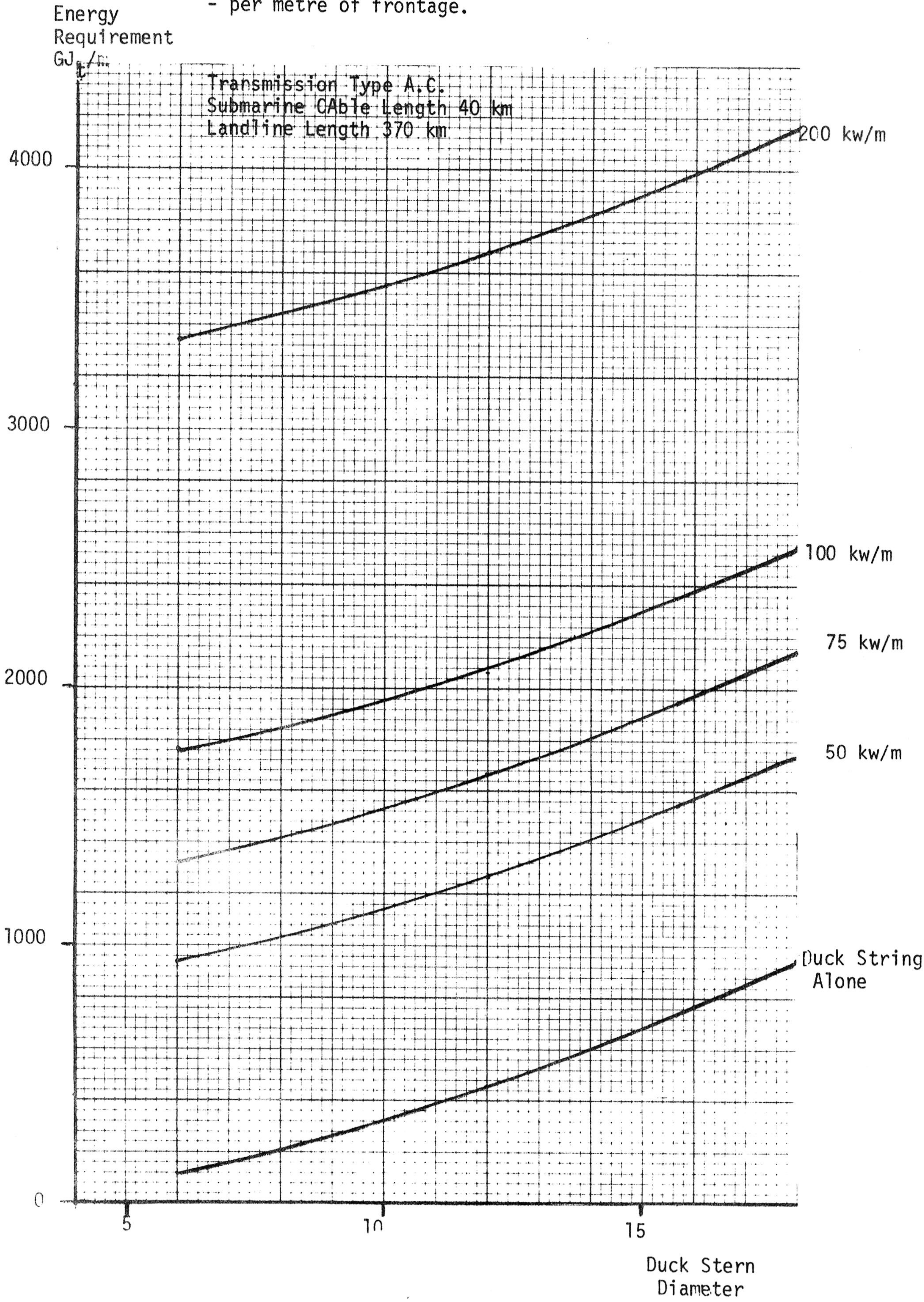


Fig. 3.

Initial Energy Requirement of a Salter Duck System
- per metre of frontage

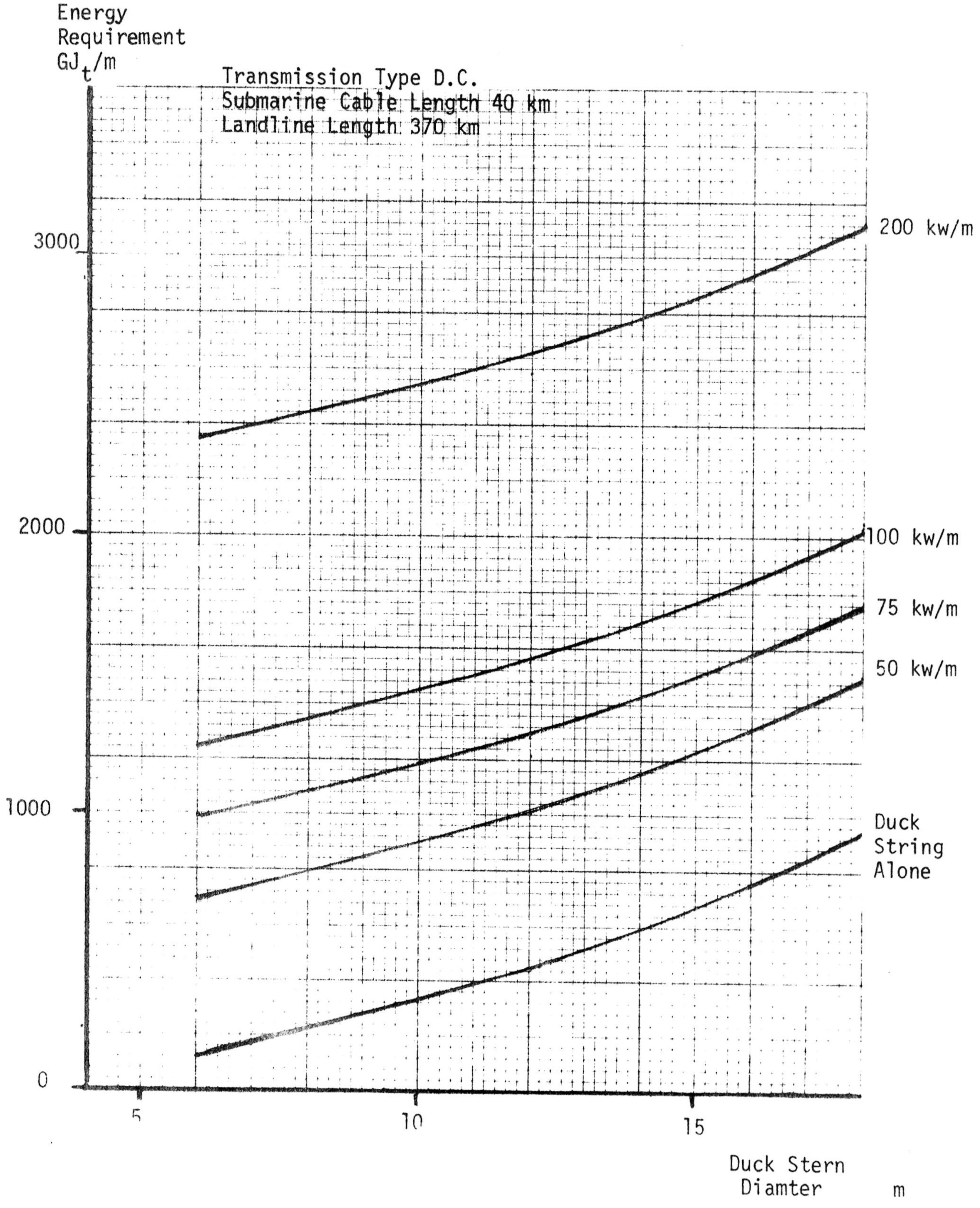


Fig. 4.

Yearly Energy Requirement of a Salter Duck System
- per metre of frontage.

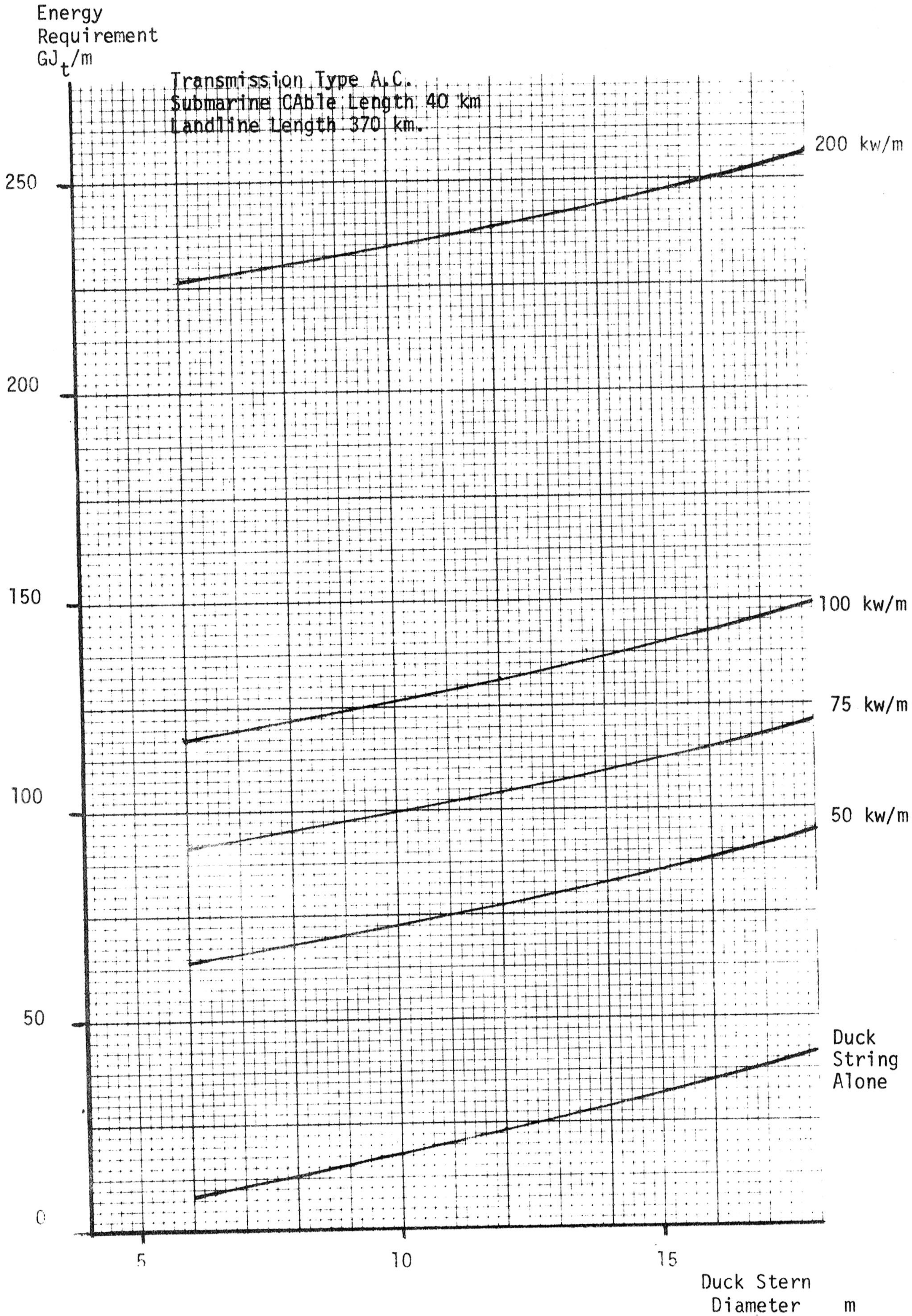


Fig. 5

Yearly energy requirement of Salter Duck System
- per metre of frontage.

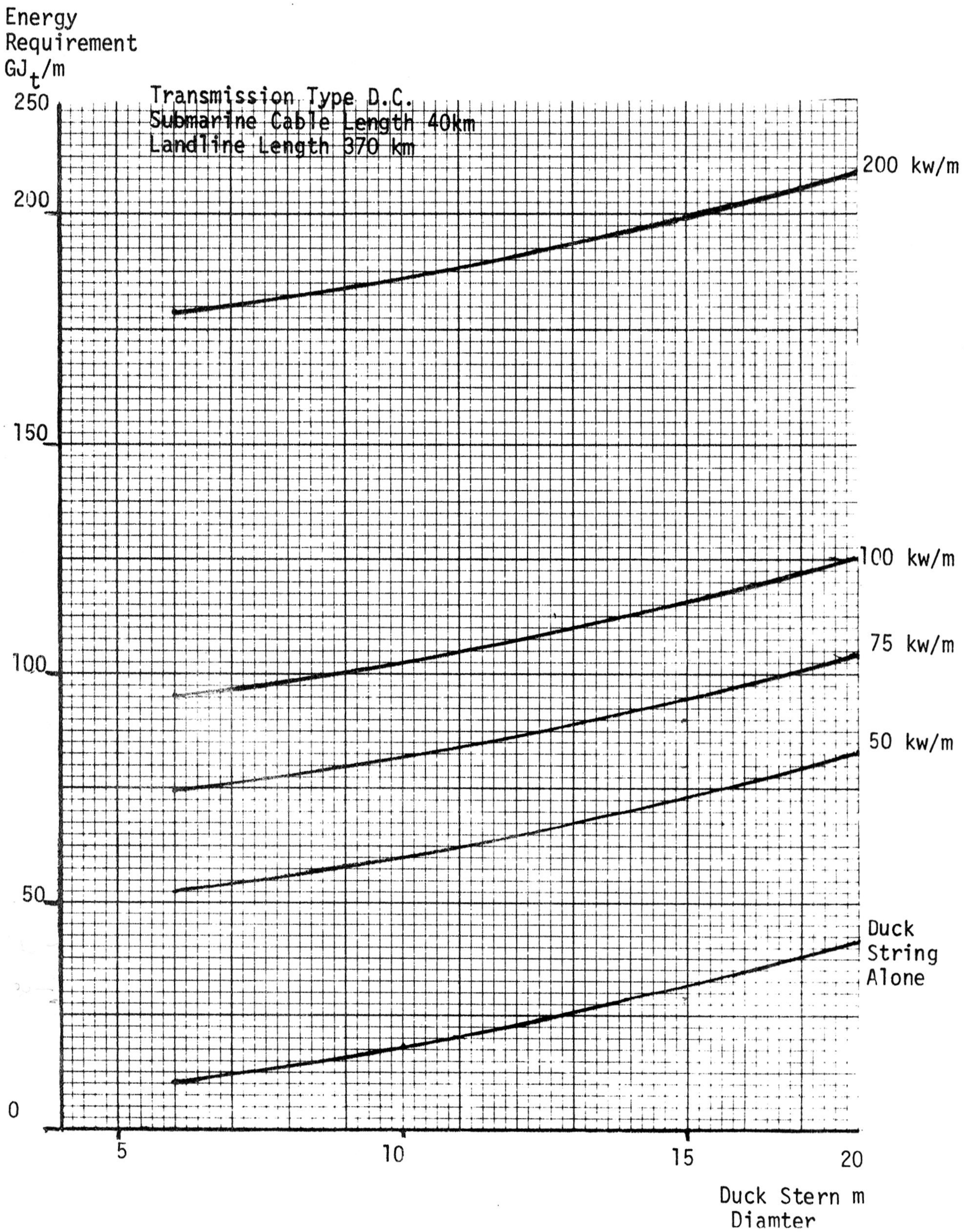


Fig. 6

Breakdown of the initial energy requirements of a Salter Duck System (per metre of frontage) VS. Duck Stern Diameter.

Power Limit 50 kw/m
Transmission Type A.C.
Submarine Cable Length 40 km
Landline Lengths 370 km

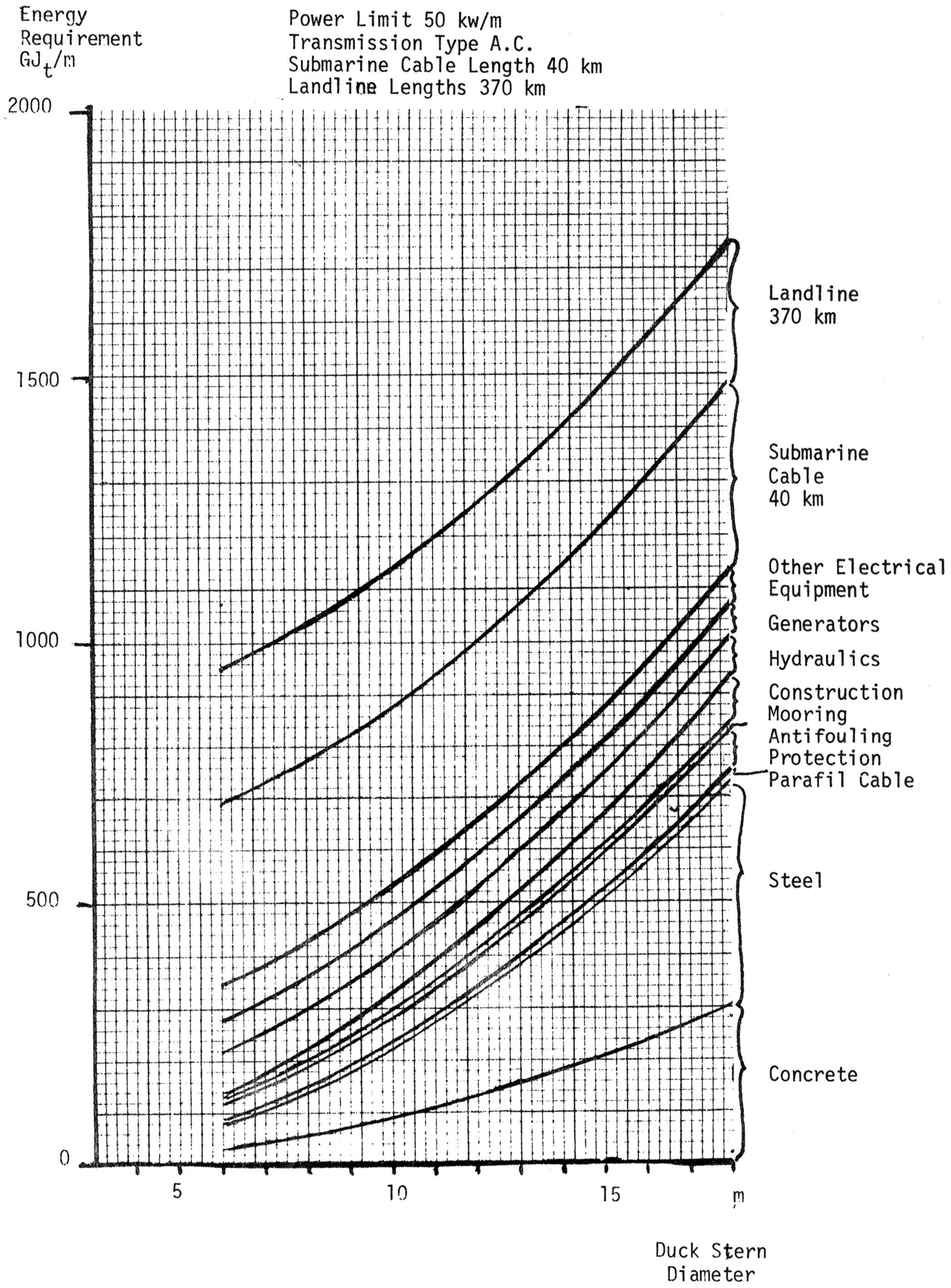


Fig. 7

Breakdown of the initial Energy Requirements of a Salter Duck System (per metre of frontage) VS. Duck Stern Diameter.

Power Limit 50 kw/m
Transmission Type D.C.
Submarine Cable Length 40 km
Landline Length 370 km

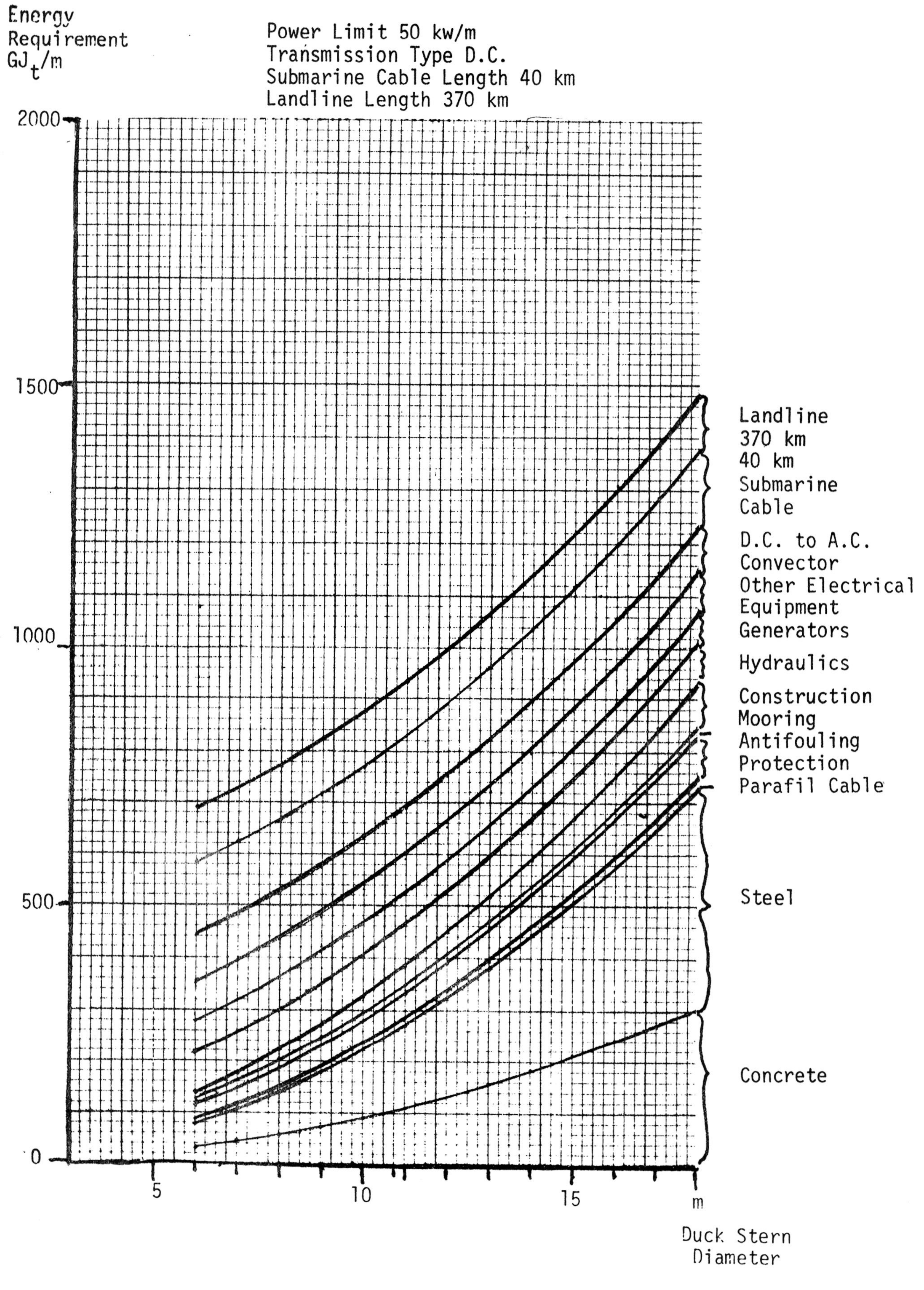


Fig. 8

Breakdown of the Yearly Energy Requirement of a Salter Duck System (per metre of fromtage) VS Duck Stern Diameter.

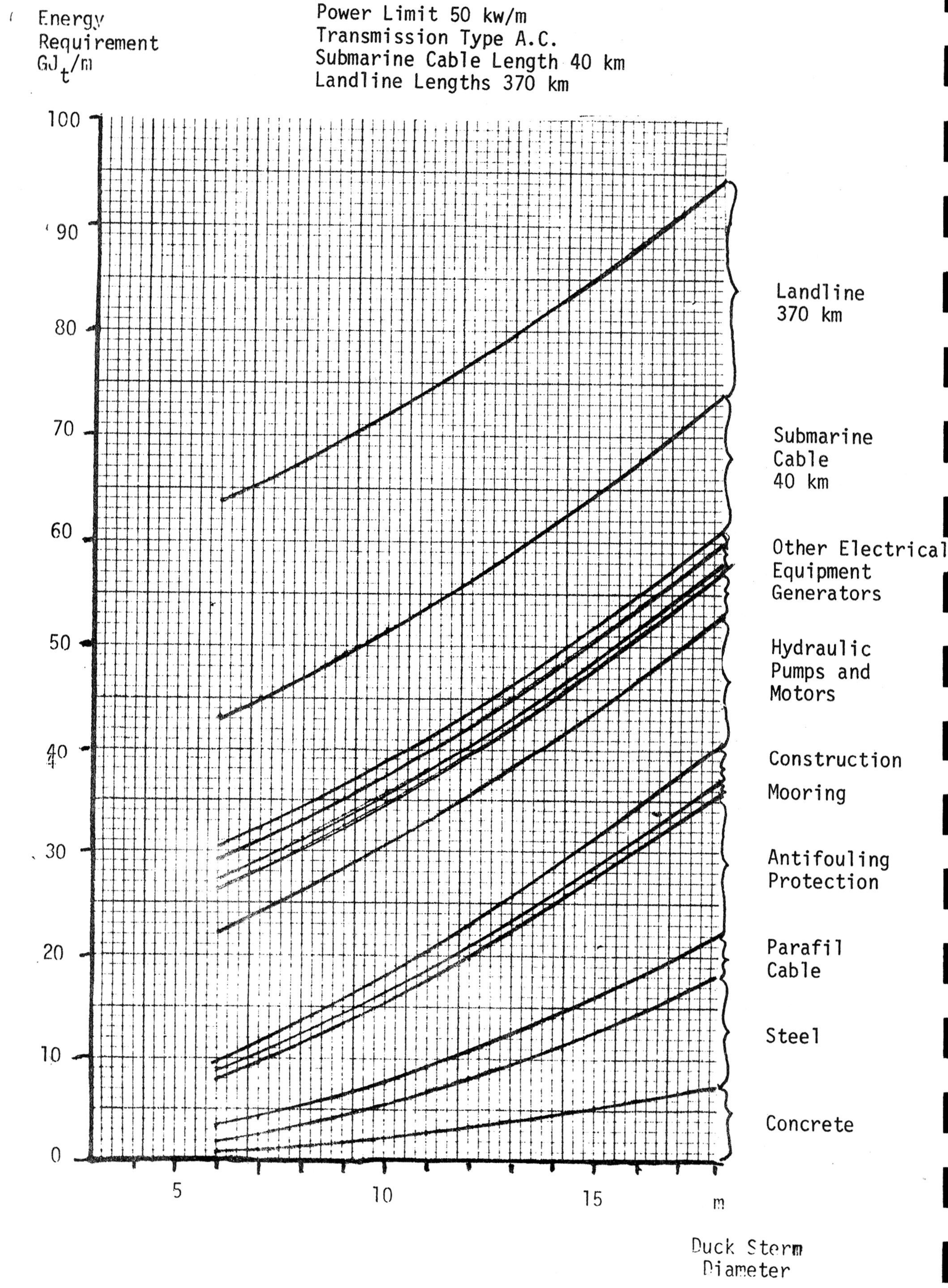


Fig. 9

Breakdown of the yearly energy requirement of a Salter Duck System (per metre of frontage) VS Duck Stern Diameter.

Power Limit 50 kw/m
Transmission Type D.C.
Submarine Cable Length 40 km
Landline Length 370 km

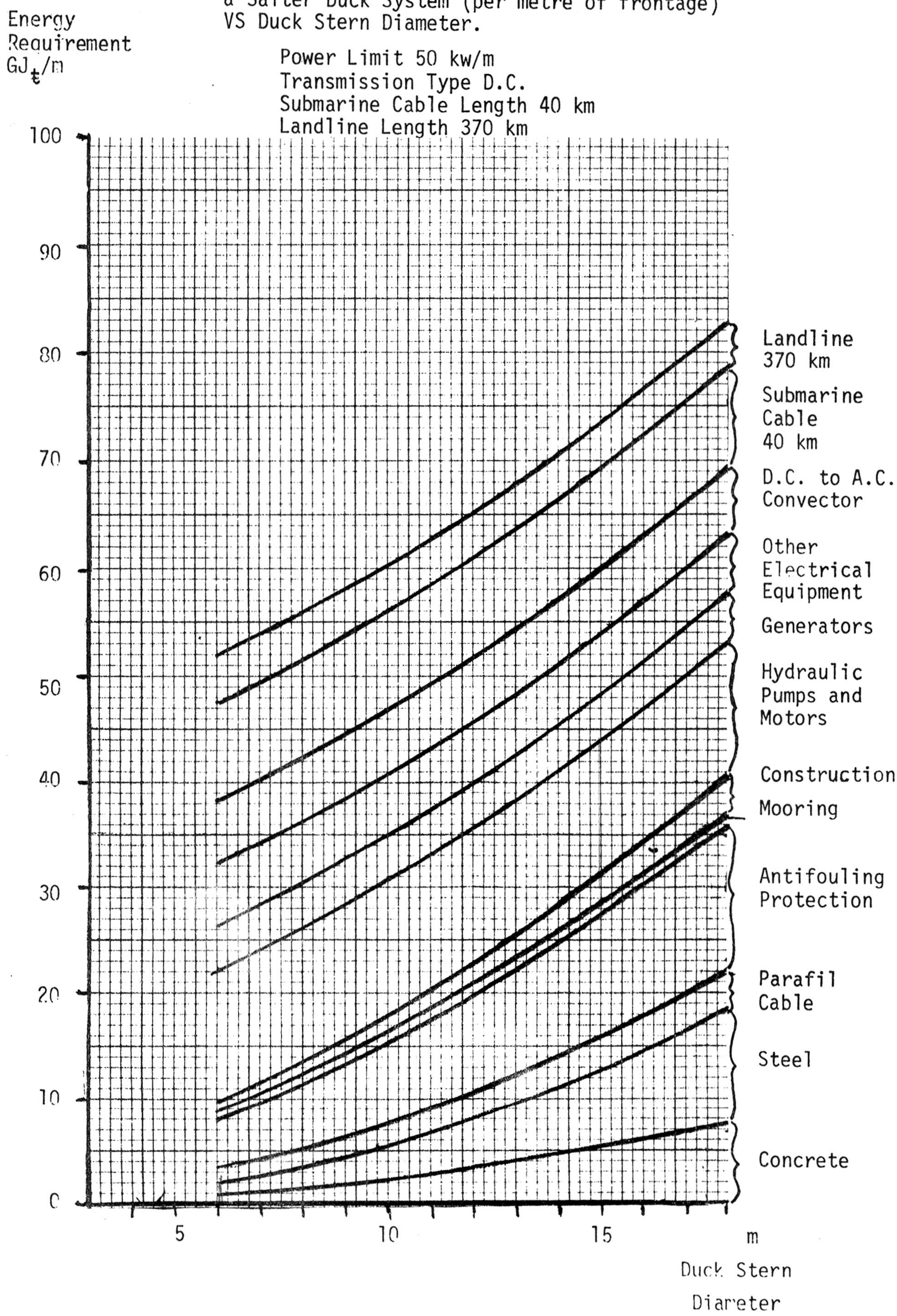


Fig. 10

Energy Payback Time vs Wave Power Extraction Efficiency for
A Salter Duck System.

Transmission Type A.C.
Energy Requirements of Submarine Cable and Landline is excluded.

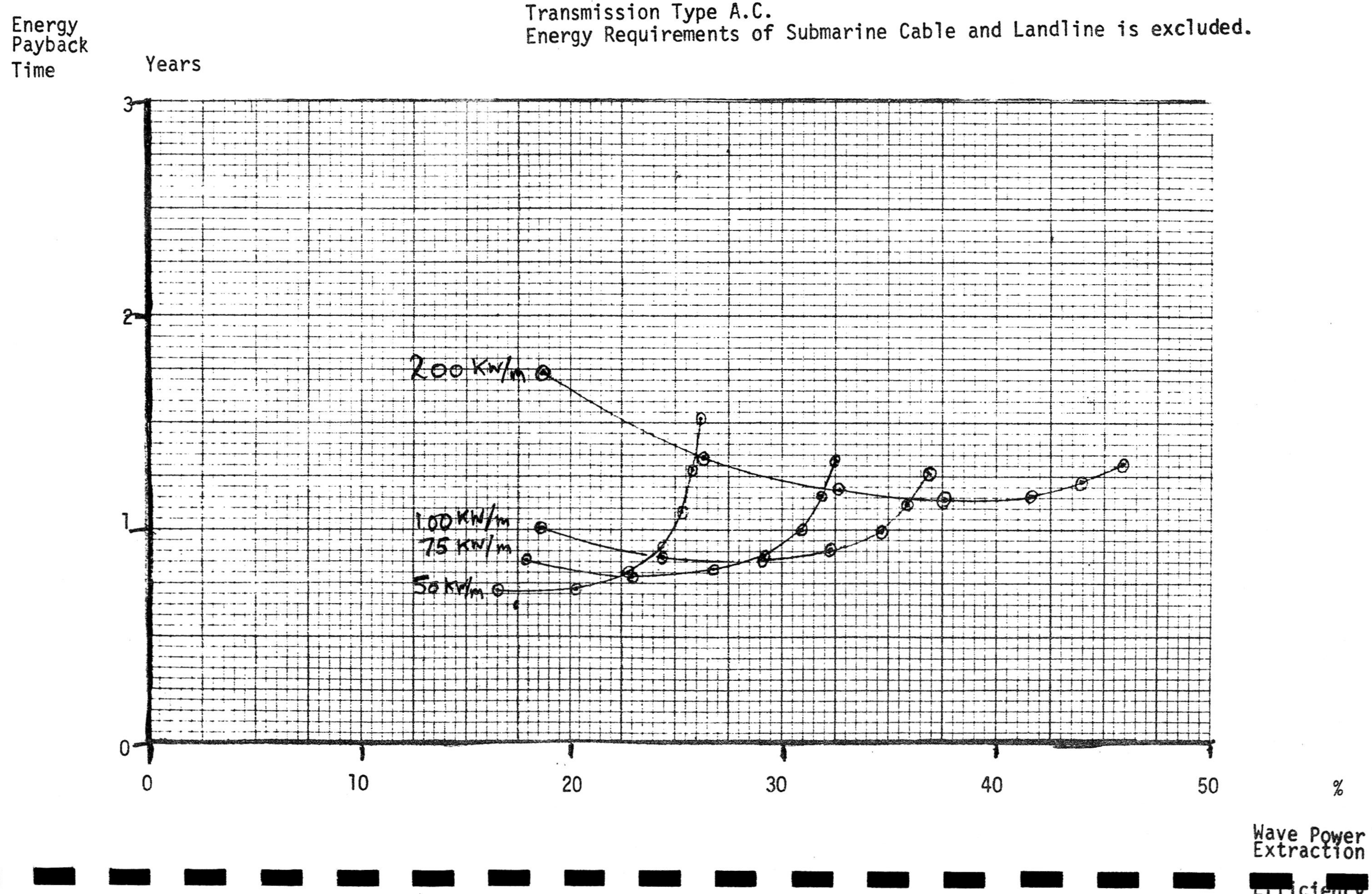


Fig. 11

Energy Payback vs Wave Power Extraction Efficiency for a Salter Duck System

Transmission Type D.C.
Energy Requirement of Submarine Cable and Landline is excluded.

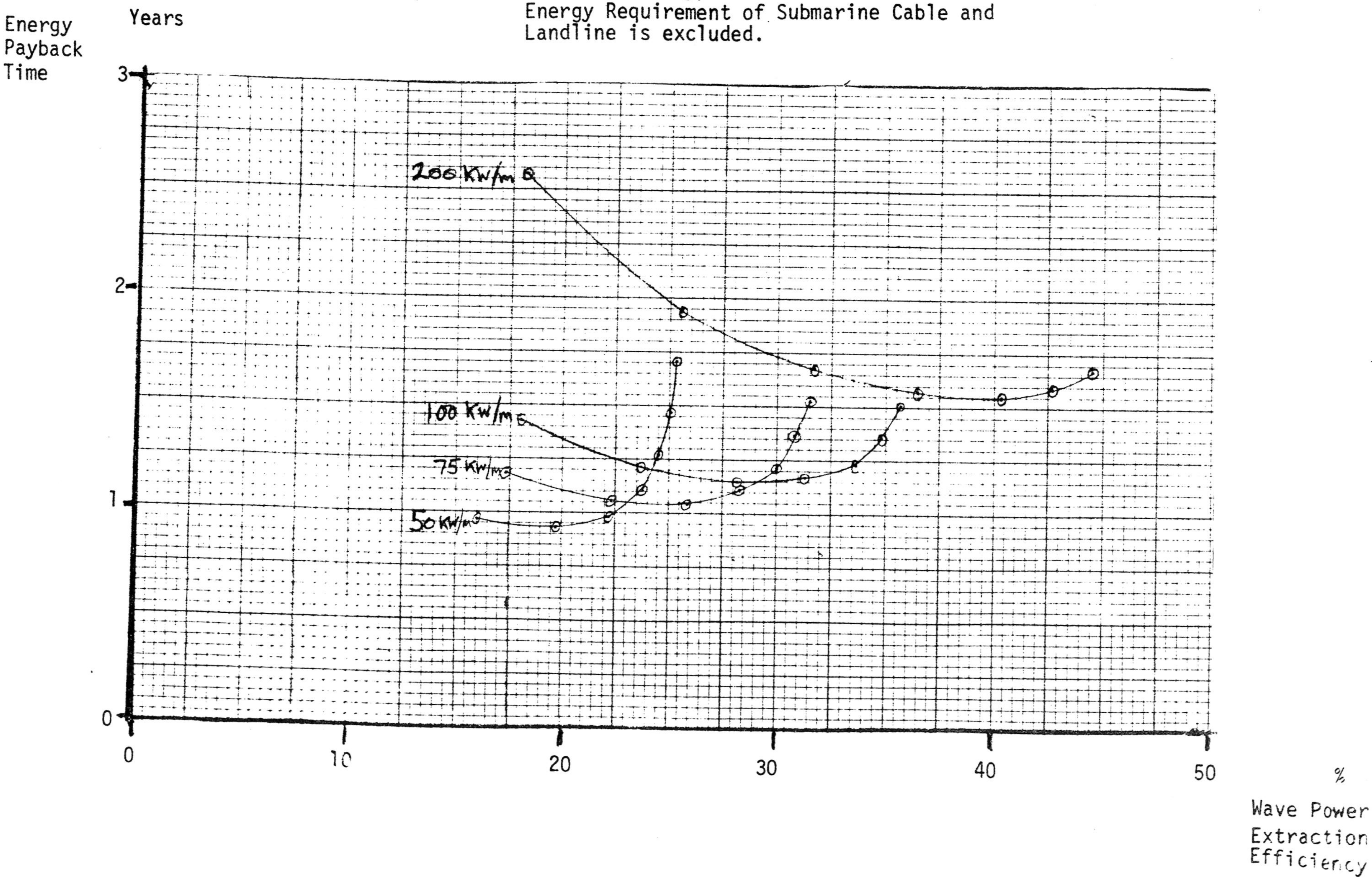


Fig. 12

Energy Payback Time vs Wave Power Extraction Efficiency for a Salter Duck System

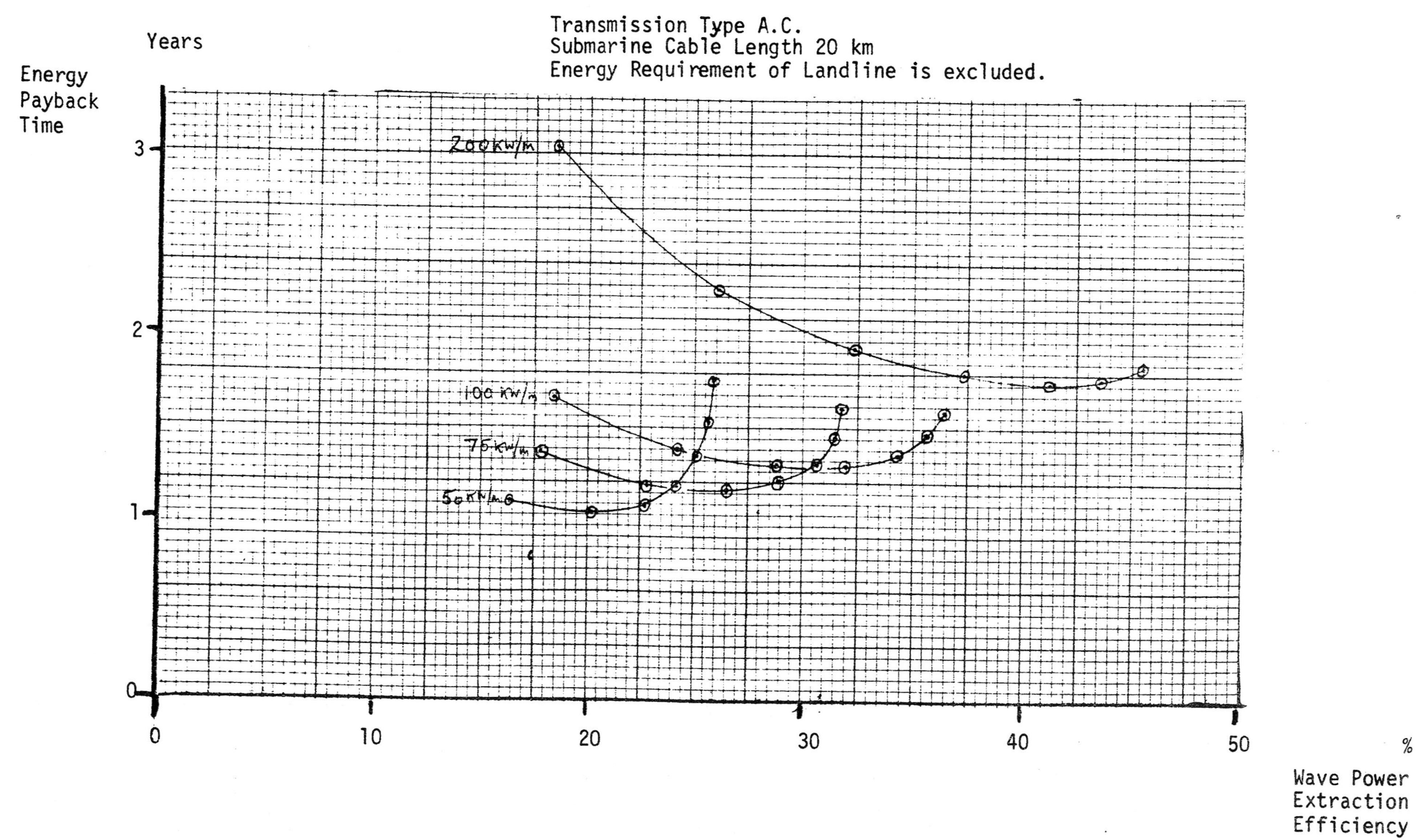


Fig. 13

Energy Payback Time vs Wave Power Extraction Efficiency for A Salter Duck System

Transmission Type D.C.
Submarine Cable Length 20 km
Energy Requirement of Landline is excluded.

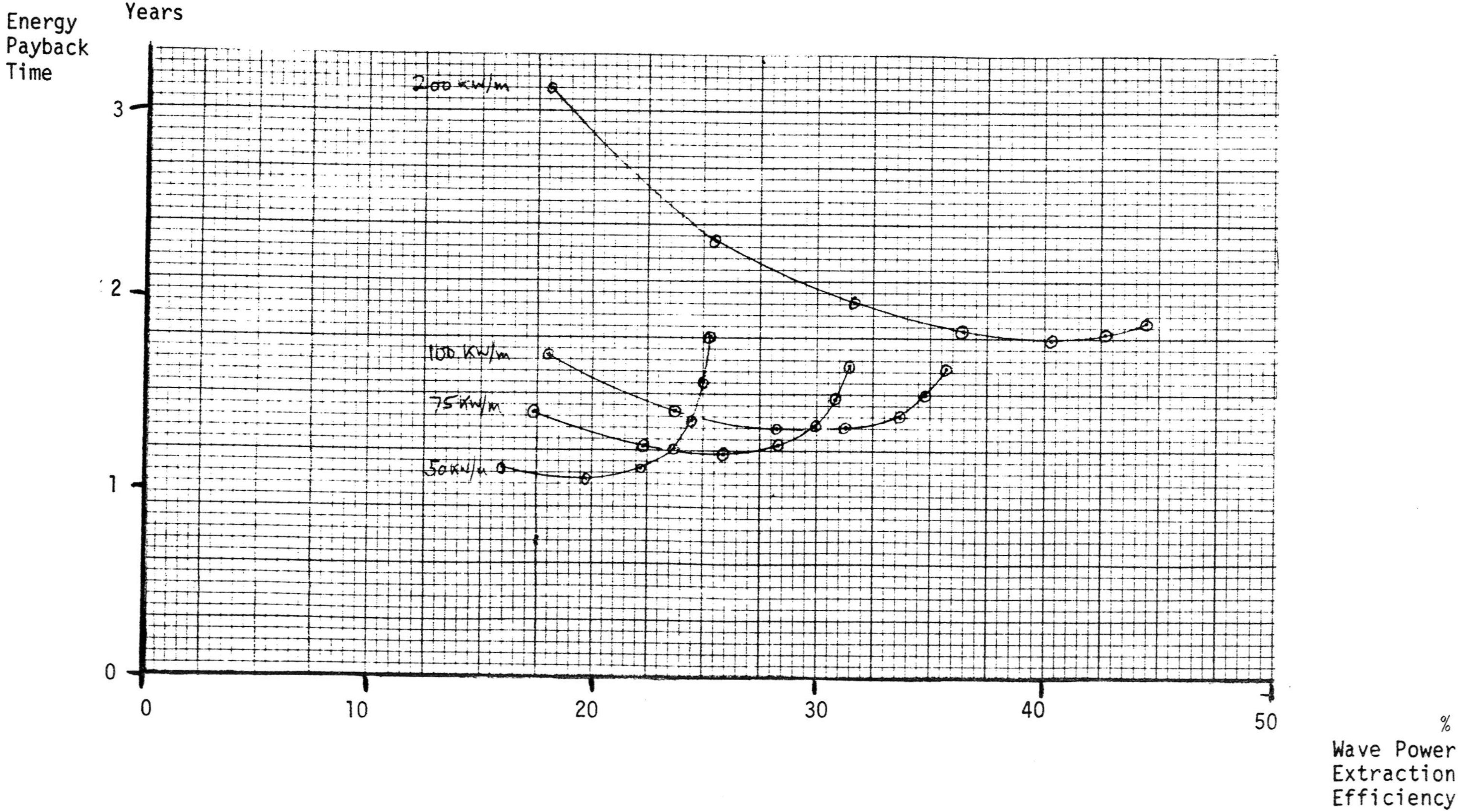


Fig. 14

Energy Payback Time vs Wave Power Extraction Efficiency for A Salter Duck System.

Transmission Type A.C.
Submarine Cable Length 40 km
Landline Length 370 km.

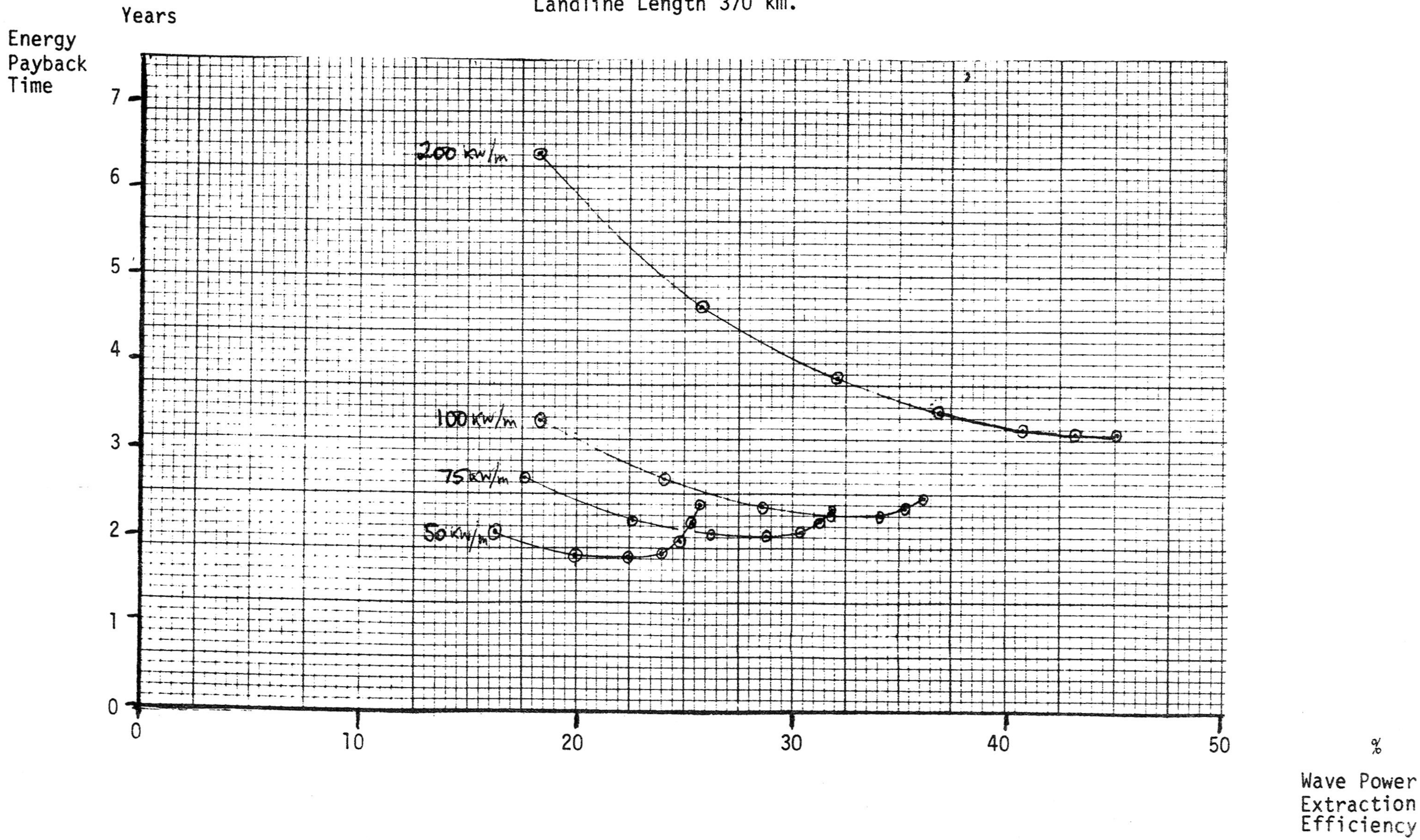


Fig. 15

Energy Payback Time vs Wave Power Extraction Efficiency for a Salter Duck System.

Transmission Type D.C.
Submarine Cable Length 40 km
Landline Length 370 km

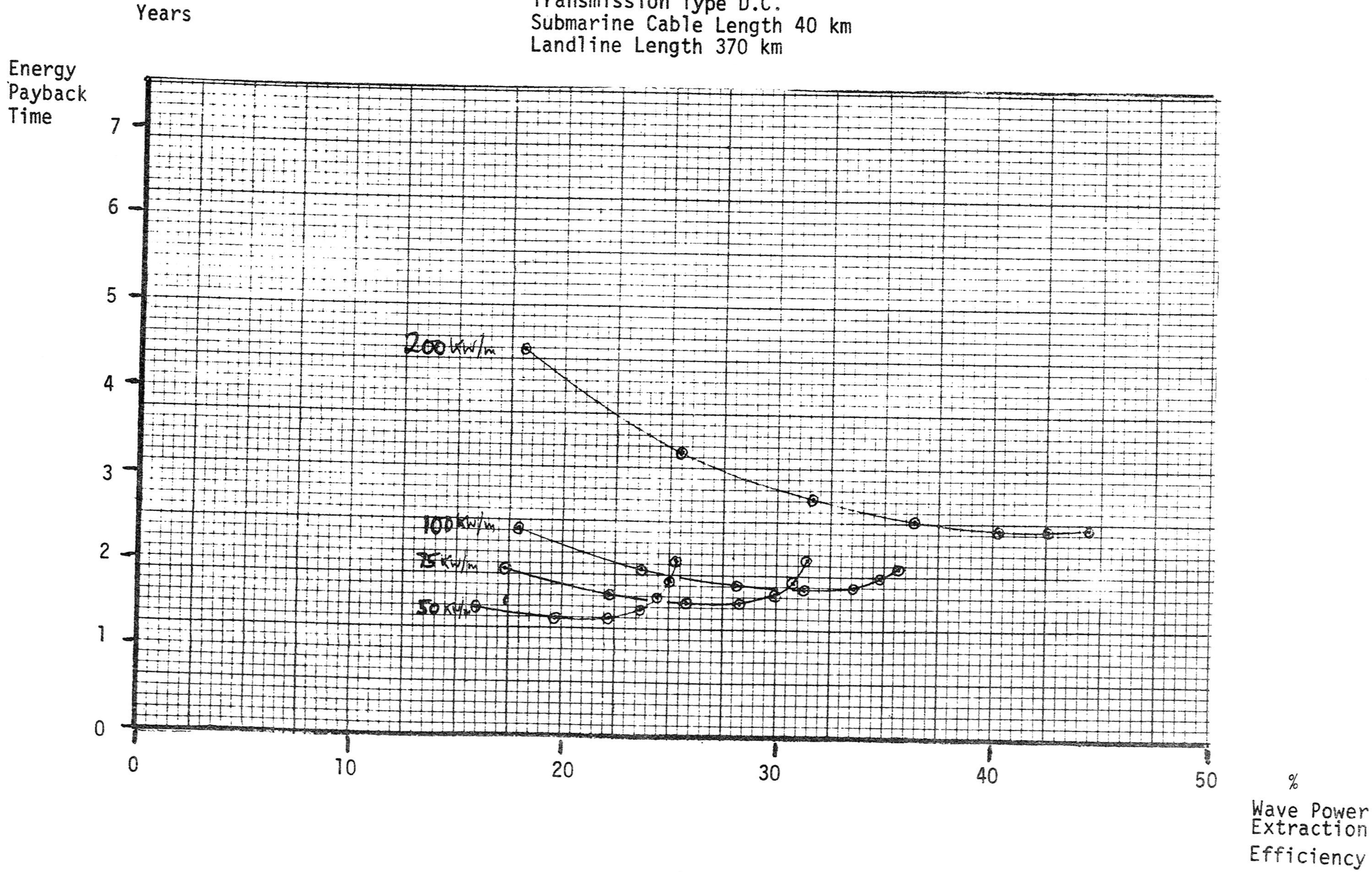


Fig. 16

Energy Ratio vs Extraction Efficiency for a Salter Duck System

A.C. Transmission
Energy Requirement of Submarine Cable and Landline is excluded.

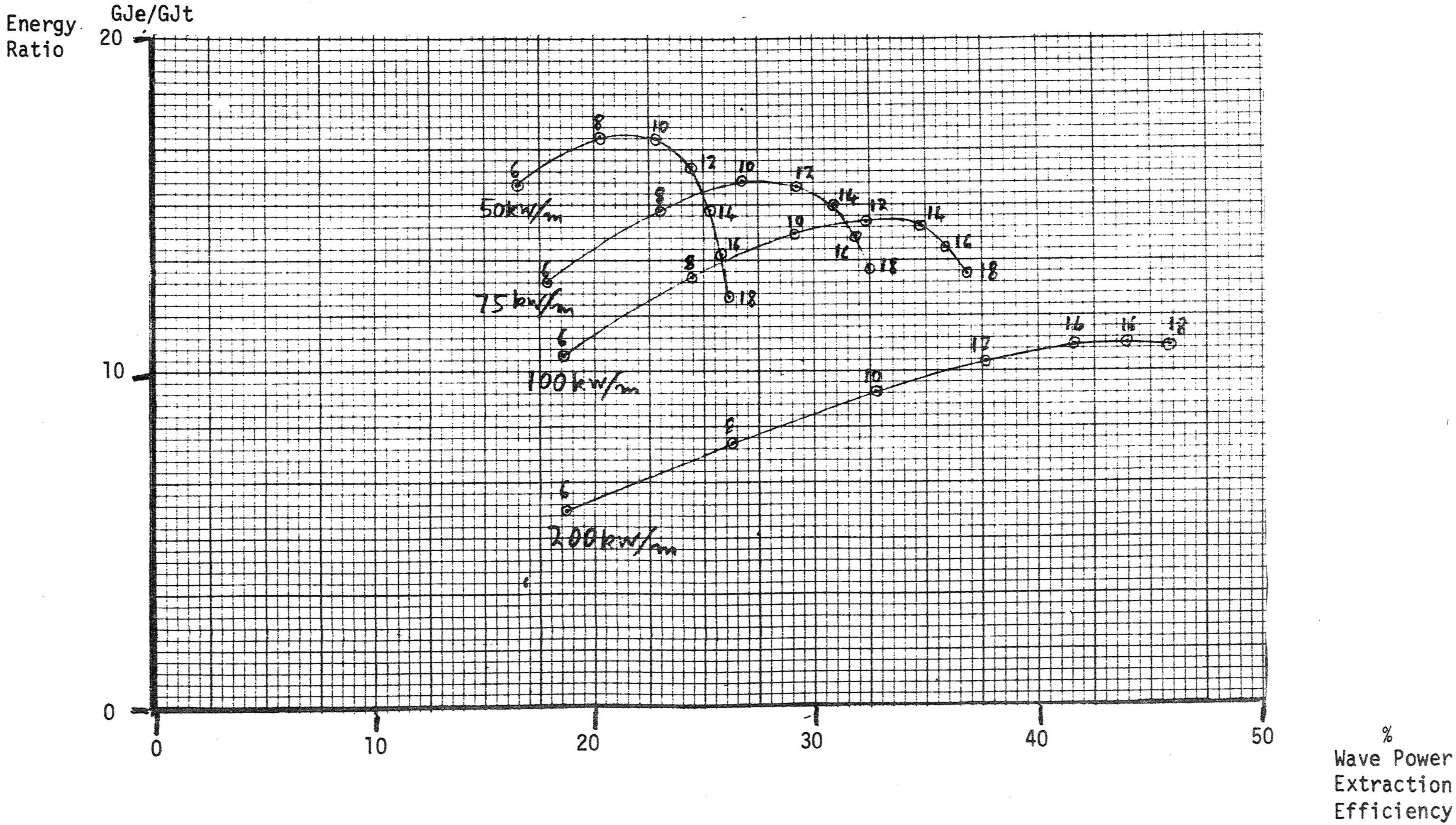


Fig. 17

ENERGY RATIO VS EXTRACTION EFFICIENCY FOR A SALTER DUCK SYSTEM

D.C. TRANSMISSION
ENERGY REQUIREMENT OF SUBMARINE CABLE AND LANDLINE IS EXCLUDED

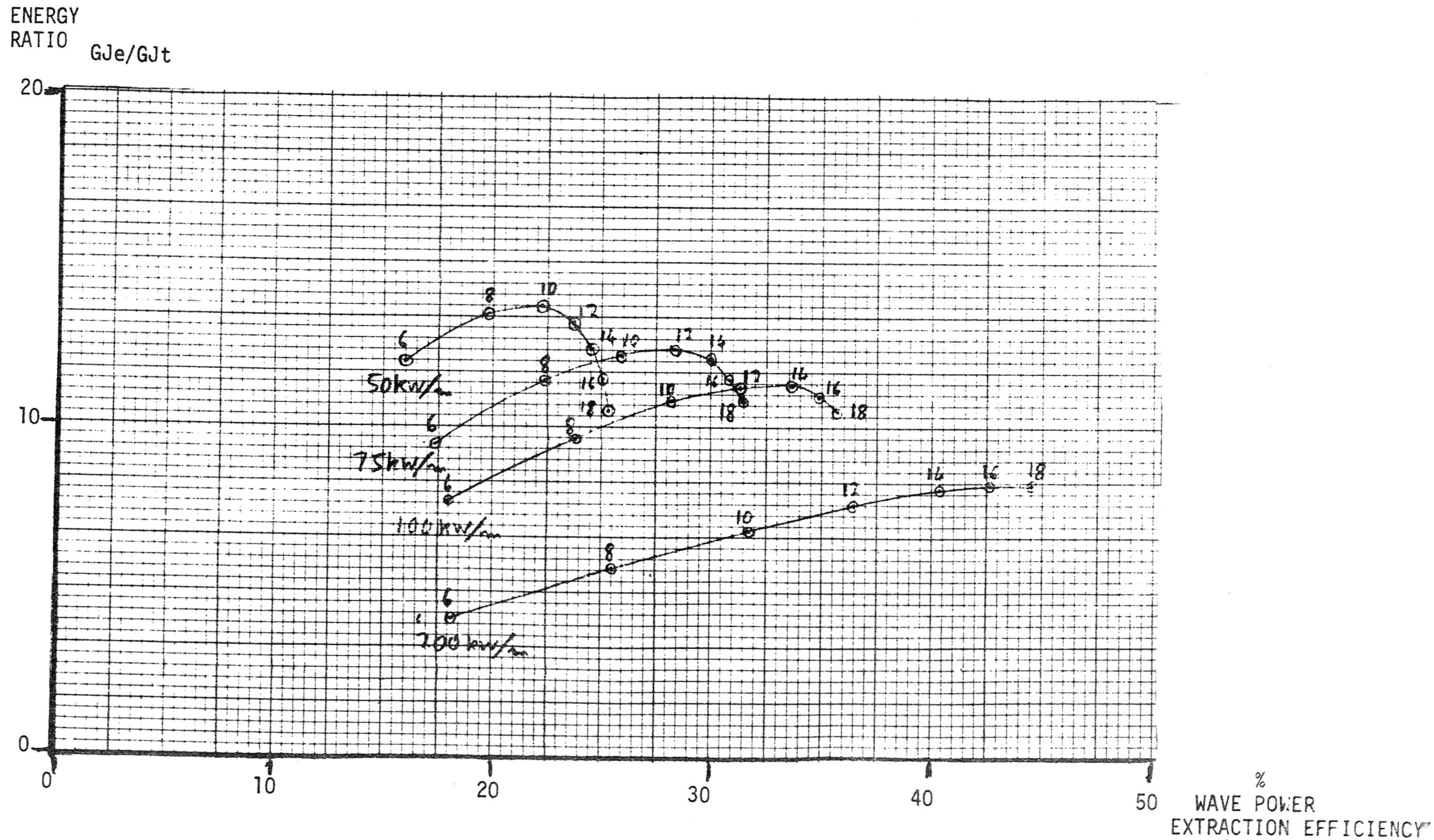


Fig. 18

ENERGY RATIO VS EXTRACTION EFFICIENCY FOR A SALTER DUCK SYSTEM

TRANSMISSION TYPE A.C.

SUBMARINE CABLE LENGTH 20km.

LANDLINE EXCLUDED

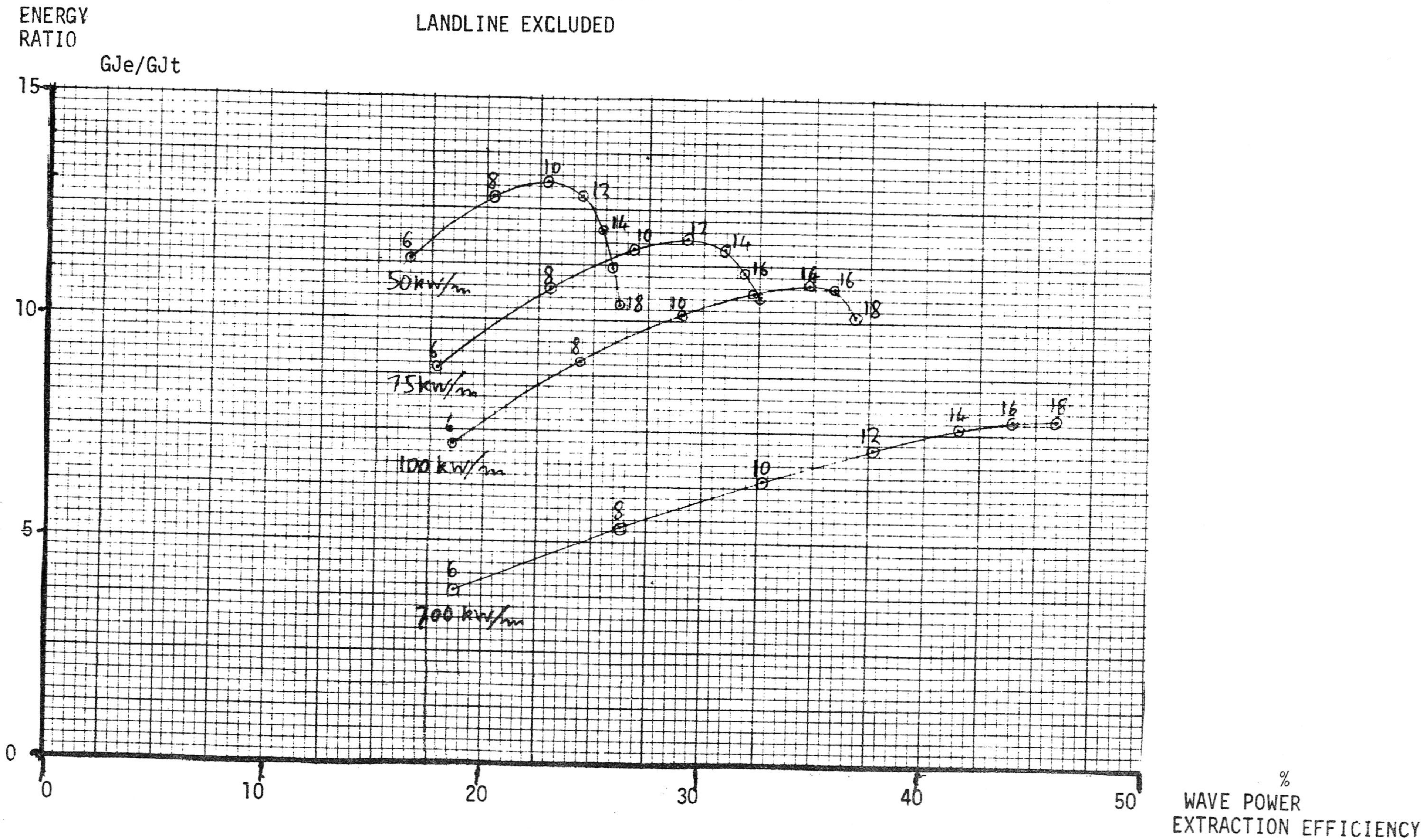


Fig. 19

ENERGY RATIO VS EXTRACTION EFFICIENCY FOR A SALTER DUCK SYSTEM

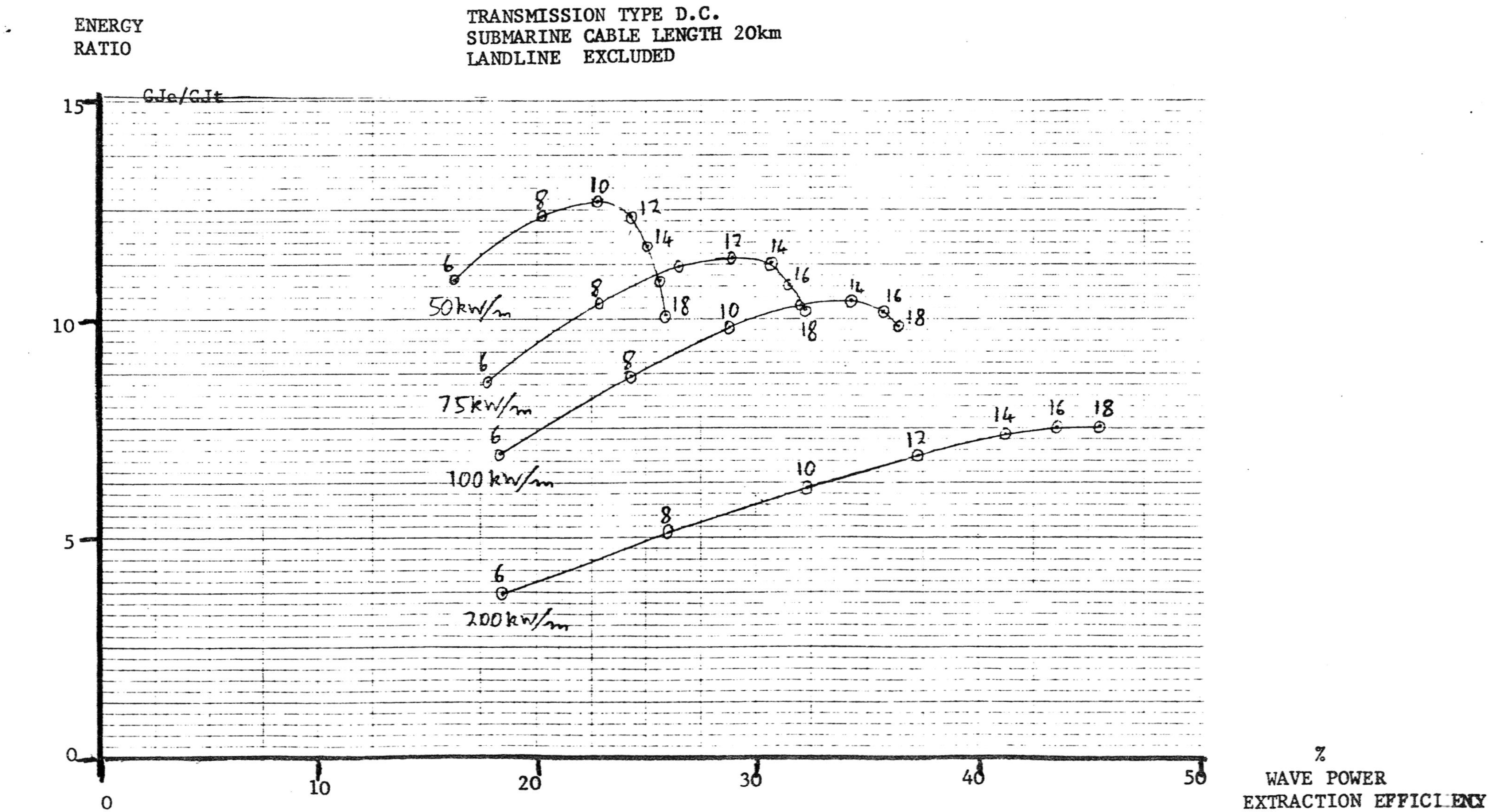


Fig. 20

ENERGY RATIO VS EXTRACTION EFFICIENCY FOR A SALTER DUCK SYSTEM

TRANSMISSION TYPE A.C.
SUBMARINE CABLE LENGTH 40km
LANDLINE LENGTH 370km

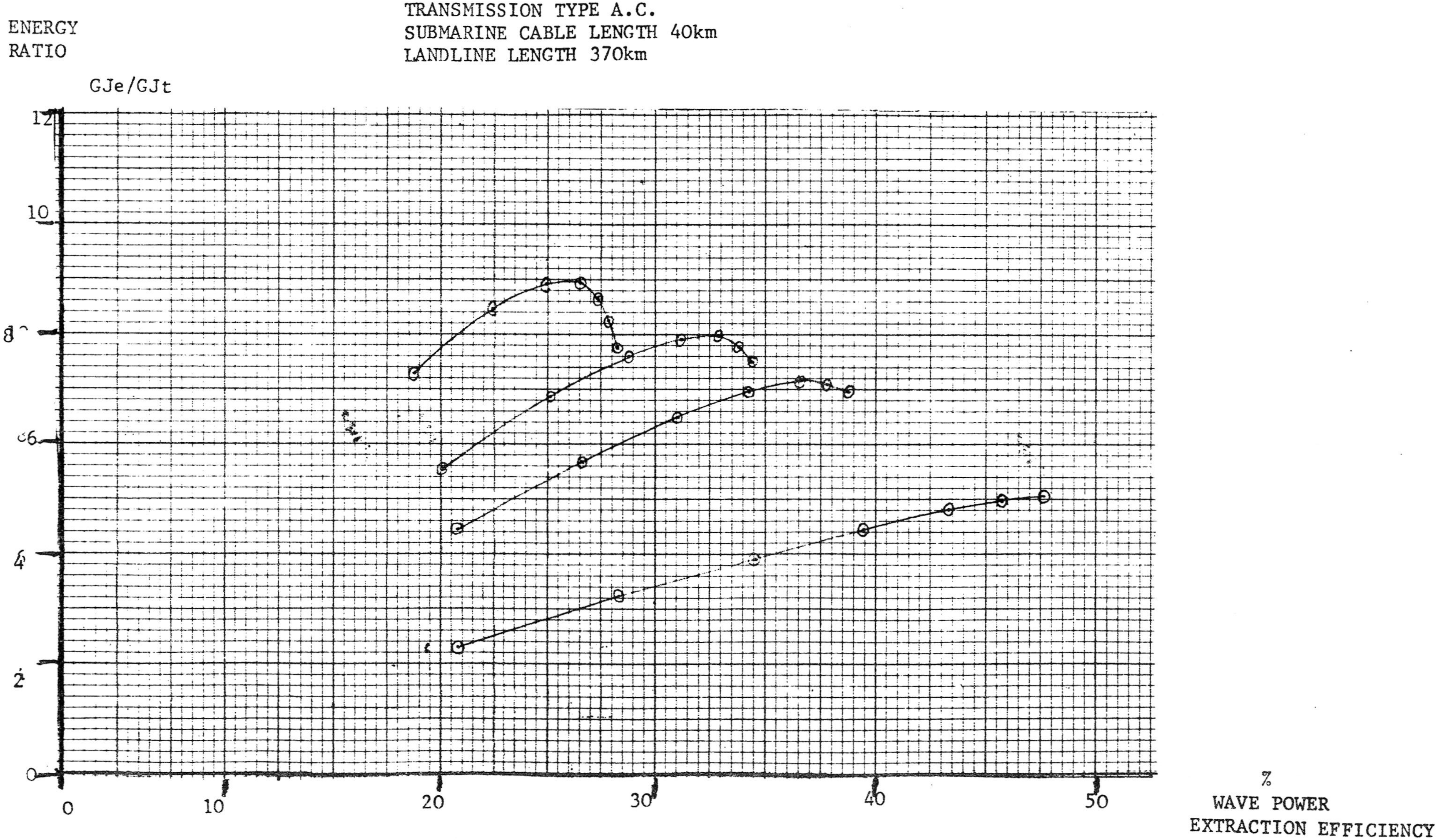


Fig. 21

ENERGY RATIO V EXTRACTION EFFICIENCY FOR A SALTER DUCK SYSTEM

TRANSMISSION TYPE DC
SUBMARINE CABLE LENGTH 40km
LANDLINE LENGTH 370km

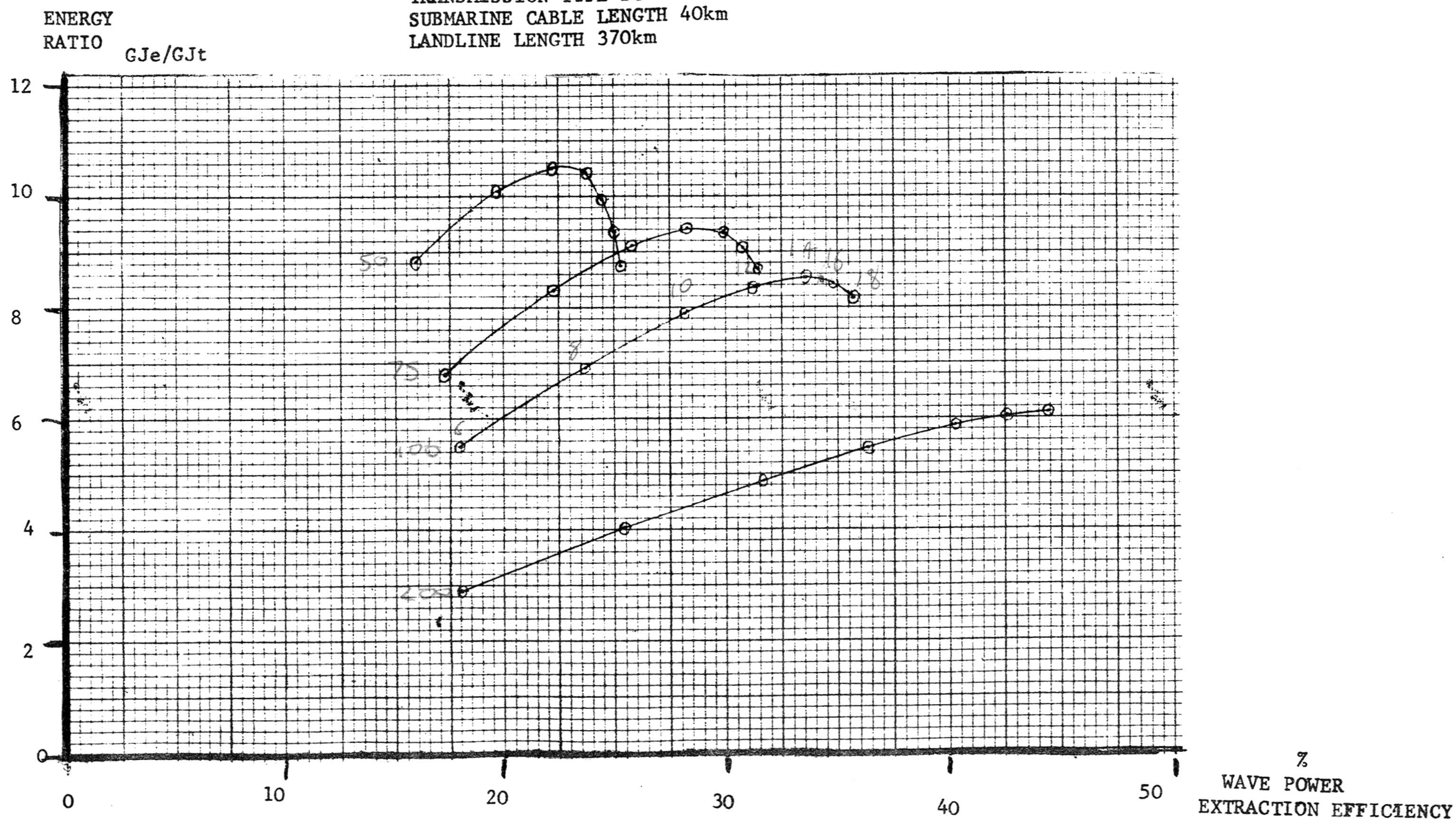
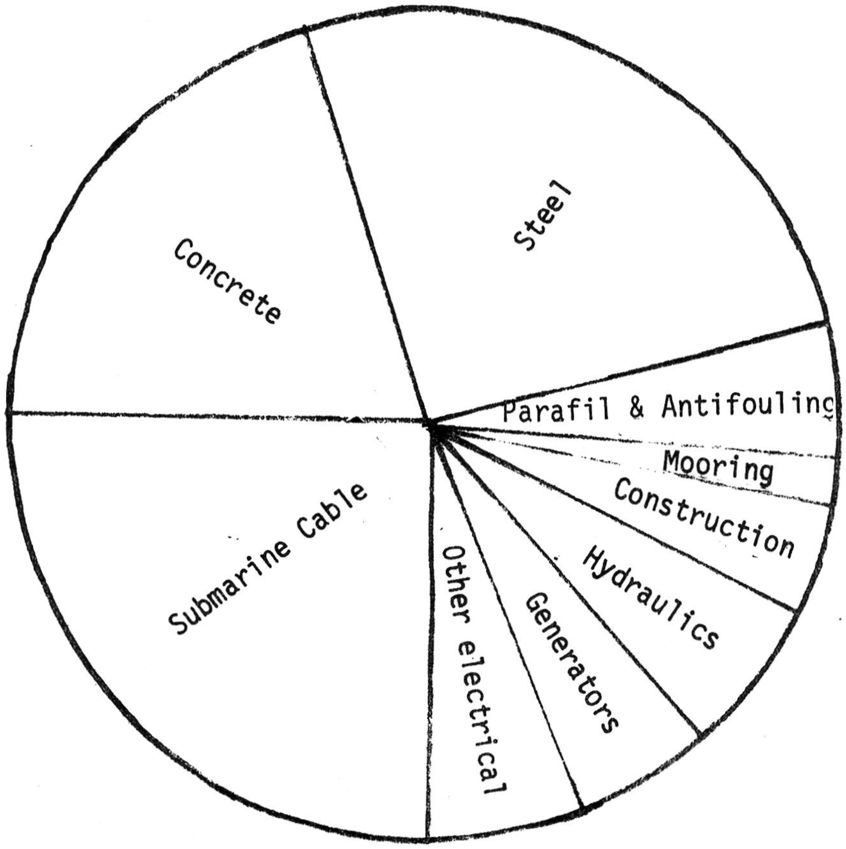


Fig. 22
A.C. System 16 m duck 15 kw/m Power Limit

Total Energy Requirement



Energy Requirement Accounted to One Years Operation

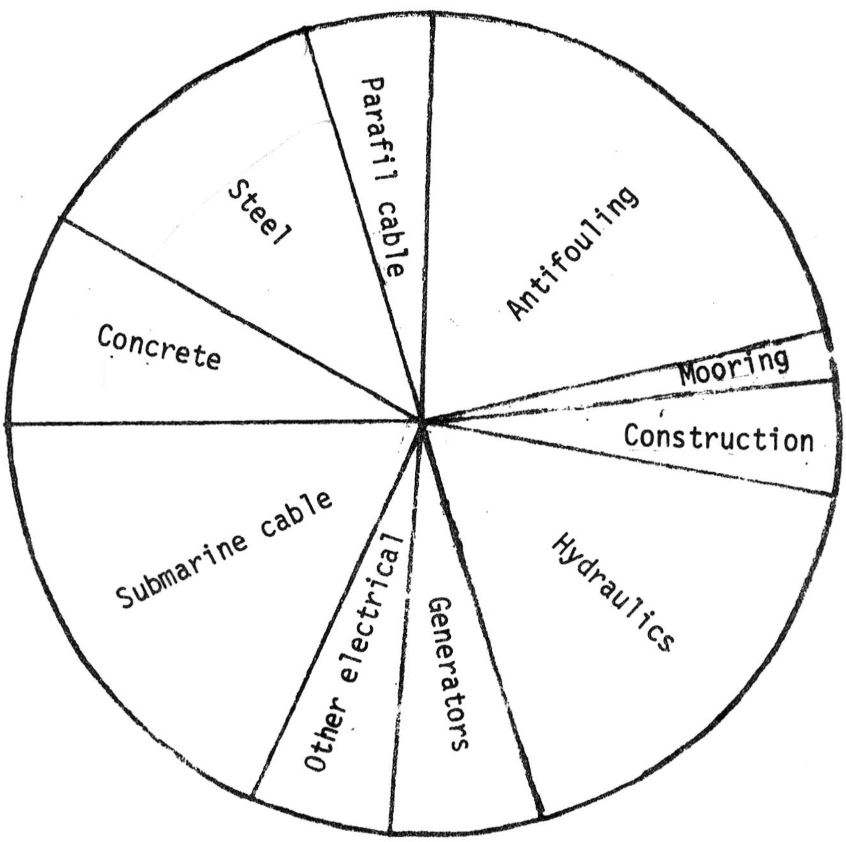
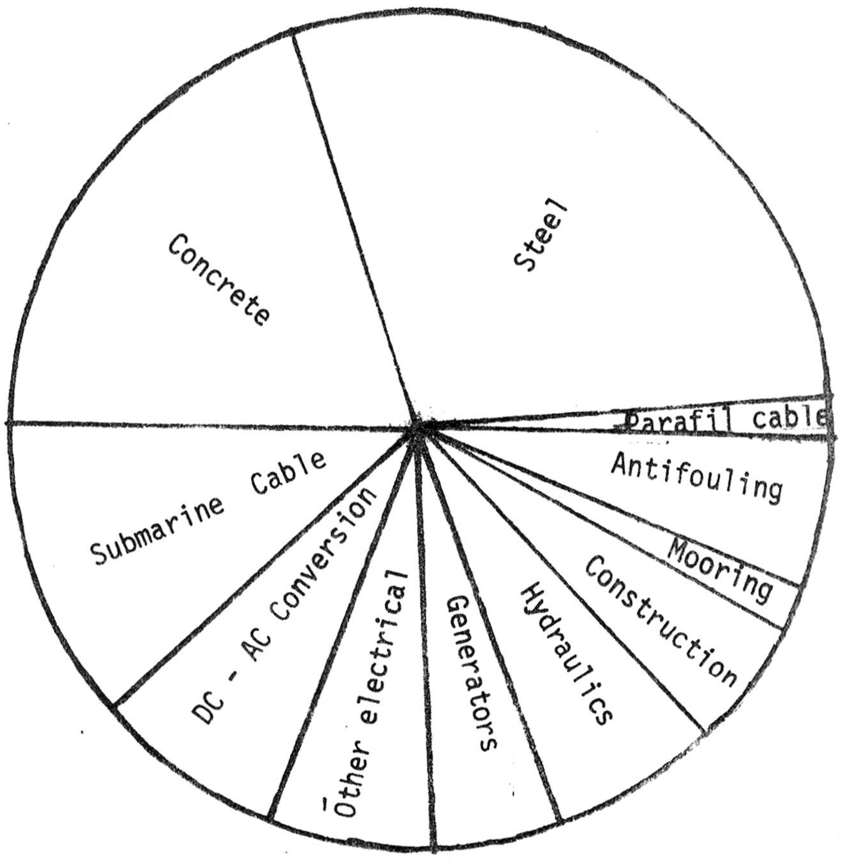


Fig. 23

D.C. System 15 m duck 50 kw/m power limite

Total Energy Requirement



Energy Requirement Accounted to One Years Operation